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Scheduling with limited resources along the
aeronautical supply chain: From parts
manufacturing plants to final assembly lines

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ABSTRACT

The aeronautical industry has suffered a continuous growth in the last years and a similar growth is expected for the near future. At the same time, it has been for long learning to cope with increasing product complexity together with the reduction in time to market, production lead times and costs.

In addition, in every industry, there is nowadays an increase in process digitization that runs in parallel to the deployment of Industry 4.0 technologies. The aeronautical industry has been ahead in the use of digital solutions from the 1960's. However, up to now, it had been focused mainly on the design phase, like the implementation of CAD systems for structural design and complex system's modeling. In consequence, other processes have consistently remained almost unaffected. That has been the case of the planning and scheduling processes. Nevertheless, handling these process in a more efficient and automatized way is a must. That need is fostered by the industry digitization, the higher product complexity and the growing level of product customization.

Although planning and scheduling problems have been widely studied since the early years of Operations Research little digital scheduling solutions are deployed in any industry. One of the reasons for this have been the lack of standard products and the complexity of the problems.

In consequence, this thesis aims to close the gap between scheduling research and its implementation, focusing on real cases from the aeronautical industry.

To begin with, this thesis provides an extensive review on the planning and scheduling problems from the aeronautical industry. Moreover, an in depth literature review has been performed and the main knowledge gaps have been identified. I believe that this on its own is already of great interests for both practitioners and production managers. For production managers because it builds a bridge between the problems in the industry and the existing research, enabling a fast identification of the existing solutions for each problems. For practitioners because it characterizes the problems in terms of the scheduling categories used in the literature and identifies research gaps that were still unexplored.

Four main planning and scheduling problem categories were identified after studying the end to end aeronautical supply chain. Only one of them had been widely studied in the existing literature. Therefore, I have studied in detail the other three that, to the best of my knowledge, had not been addressed yet. For each of them, I have translated the business needs into requirements and made a model proposal. Moreover, experimentation has been performed with industrial instances, solving them in times suitable for the real implementation in most cases.

The first models provided were deterministic. Thus, this work would have been insufficient if no uncertainty had been taken into account. In consequence, one additional part is dedicated to it, using two different approaches: discrete event simulation and re-scheduling.

In the last part, I share some conclusions on the data structure and exchanges that are necessary for the previous model's implementation in the aeronautical industry. A flexible and

fluent information share between systems is crucial for Industry 4.0 implementation. Therefore, this data mapping is a must for a smooth implementation of any scheduling system within a real industrial environment.

RESUMEN

La industria aeronáutica ha sufrido un gran crecimiento en los últimos años y las previsiones apuntan hacia crecimientos similares para los próximos años. Al mismo tiempo, los desarrollos de nuevos aviones se han vuelto cada vez más exigentes: se han acortado los tiempos de entrega a la par que han aumentado los requerimientos en términos de eficiencia y equipamiento de las aeronaves.

Por otra parte, se está viviendo una creciente digitalización de los procesos en cualquier industria, acompañada de la implantación de las tecnologías de la Industria 4.0. El sector aeronáutico ha sido de los pioneros en la implantación de herramientas digitales desde los años 60. Sin embargo, la mayoría de los esfuerzos se habían centrado hasta ahora en el área de diseño, como el uso intensivo de sistemas CAD para el diseño estructural y para el modelado de sistemas complejos. Por tanto, otros procesos han continuado siendo altamente manuales. Uno de ellos es el de planificación y programación de la producción. No obstante, existe una acuciante necesidad de realizarlos de una manera más eficiente y automatizada. Esto se debe tanto al aumento de la digitalización como al aumento de la complejidad y la personalización de los productos.

Aunque los problemas de planificación y programación se han estudiado desde los comienzos de la investigación operativa, existen muy pocos ejemplos de soluciones reales implementadas a nivel industrial, no sólo en la industria aeronáutica. Una de las causas de esta ausencia es la falta de soluciones estándar, así como la complejidad de los problemas a tratar.

En consecuencia, el objetivo de esta tesis es cerrar la brecha entre los problemas estándar de planificación y programación de la producción y su implantación real, aplicando las soluciones a la industria aeronáutica.

En primer lugar, esta tesis presenta una revisión extensa de los problemas de planificación y programación de la producción dentro de la industria aeronáutica. La descripción de los problemas se acompaña de una revisión de la literatura, con objeto de identificar qué problemas se habían tratado previamente y cuáles estaban aún sin explorar. Esta clasificación ha sido la primera contribución de la tesis, tanto para el mundo académico como para el industrial. Para la industria porque ordena los problemas permitiendo una rápida identificación de las soluciones ya disponibles. Para la parte académica porque al ordenar los problemas en términos de las categorías utilizadas en la literatura muestra de forma clara los temas que no habían sido tratados hasta el momento.

En esa primera revisión, se identificaron cuatro grandes categorías de problemas de planificación y programación de la producción en la industria aeronáutica. Salvo uno de ellos, el resto no se habían abordado hasta ahora o se habían tratado de forma incompleta. Por tanto, los otros tres se han tratado en detalle a lo largo de la tesis, traduciendo las necesidades de la industria en requerimientos y proponiendo modelos para su resolución. Además, se han probado los modelos con casos de uso reales, que han sido resueltos en tiempos válidos para una implantación industrial en la mayor parte de los casos.

Si bien el primer tratamiento de los problemas ha sido desde el punto de vista determinista, se ha dedicado otra parte al estudio de alternativas para tener en cuenta la incertidumbre inherente a la realidad industrial. Este tratamiento de la incertidumbre se ha abordado desde dos perspectivas: la simulación de eventos discretos y la replanificación.

Para finalizar, el último capítulo presenta las implicaciones que tendría la implantación de estos modelos en términos de estructura de datos y conexión con otros sistemas. Entiendo que esta reflexión es una parte fundamental para asegurar una correcta explotación de cualquier nueva herramienta y más aún en el entorno actual de digitalización e Industria 4.0.

DEDICATION

Dice un proverbio africano que 'hace falta una aldea entera para criar a un niño'. Casi una aldea ha hecho también falta para llevar esta tesis a buen puerto. Es difícil enumerar a todas las personas que me han apoyado durante su desarrollo.

Gracias a mis padres por cada día confiar y creer en mí y en mis expectativas. Por esforzarse desde hace años para que tuviera todas las oportunidades que me han traído hasta aquí. Y, en esta última etapa, por todas las horas cuidando de los nietos que han hecho esta tesis posible.

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Part I

General Introduction

INTRODUCTION

1.1 Context: Industry 4.0

Nowadays, industries are facing a new era of extraordinary challenges. End users are increasingly asking for customized products and, at the same time, product life-cycles get shorter. In addition, the impact of industrial production on the environment is severe and the consumption of non-renewable resources needs to be reduced. Therefore, the achievements of more flexible, agile and efficient production systems is a must [Wang et al., 2016c].

Triggered by these and other challenges and thanks to the introduction of the Internet of Things and services into the manufacturing environment, there is an upcoming fourth industrial revolution that has been named Industry 4.0 [Kagermann and Wahlster, 2013].

In the late 18th century, the introduction of water and steam powered mechanical manufacturing led to the first industrial revolution. One century later, in the early 20th century a second revolution was driven by electrically-powered mass production of goods based on the division of labor. More recently, in the 1970s, the introduction of programmable logic controllers (PLC) enabled digital programming of automation systems, giving light to the third industrial revolution. The most recent revolution is triggered by the introduction of the Internet of Things and services into the manufacturing environment, which will allow the communication between machines and humans in the way of Cyber-Physical-Systems (CPS) throughout large networks. [Brettel et al., 2014]. This revolution was named as Industry 4.0 in Germany in 2011. [Kagermann et al., 2011]. Nevertheless, similar ideas have arisen all over the world, such as the *Industrial Internet* in the USA [Evans and Annunziata, 2012] or the *Digital Virtual Enterprise* named by Pratt & Whitney Canada. This four industrial revolutions are summarized in Figure 1.1.

Figure 1.1: The Four Stages of Industrial Revolutions - [Roser, 2017]

Industry 4.0 means a global integration of all the activities of the enterprise. Bitcom [Bitkom, 2015] divides this integration into horizontal, vertical and end-to-end engineering integration. This integration is enabled by the extensive use of already merging technologies. BCG, [Geissbauer et al., 2016] has identified the main nine technologies, which are shown on Figure 1.2.

- IoT.
- Cybersecurity.
- Additive Manufacturing.
- Autonomous Robots.
- Big Data Analytics and advanced Algorithms.
- Horizontal and Vertical Systems Integration: Integration needs to be supported by systems integration.
- Augmented Reality.
- Cloud Computing.
- Simulation.

Industry 4.0 means a deep transformation for the whole enterprise. Smart factories constitute a key feature for that transformation. They must be capable of managing complexity being at the same time more flexible, more efficient and greener. To do so, they integrate physical objects with information systems such as PLM (Product Life Management), MES (Manufacturing Execution systems) and ERP (Enterprise Resource Planning) [Wang et al., 2016b].

Figure 1.2: Industry4 0 Nine Technologies [Lydon, 2016]

This thesis is focused on the aeronautical industry and, in particular, on the study of some case studies from aeronautical production lines. Aeronautics is one of the European Union's key high-tech sectors on the global market. The European Union is a worldwide reference in the production of civil aircraft, including helicopters, aircraft engines, parts and components. As a result, this sector provides more than 500,000 jobs and generated a turnover of close to EUR 140 billion in 2013. This means that 34% of the employments on the sector worldwide are based in the European Union and the 43 % of the revenues worldwide are generated in the European Union.

In spite of the aeronautical industry's current size in the European Union, this industry has recently gone through big challenges. Murman, [Murman et al., 2000], provides an overview of them. From the Second World War to the 1990's, this industry had strongly relied on public investment. The end of the Cold War prompted drastic reductions in defense procurement budgets resulting in reduced military markets. The defense industry could no longer justify the cost-plus mentality that characterized the Cold War era and faced the challenge of seeking new markets.

At the same time, passenger demand fell down following the Gulf War, forcing airlines to cancel or postpone civil aircraft orders, whereas in the previous years civil aircraft orders had been running at unprecedented high levels. The inability of the industry to respond to unexpected changes in demand was reflected by long lead times. From then on, aircraft manufacturers had to learn to cope with increasing product complexity, and the reduction in time to market, production lead times and costs [Mas et al., 2015b], [Dong et al., 2010]. In fact, the aeronautical industry needs to deal with complexity in several areas:

- Modern aircrafts are built using more than 700.000 parts (not taking into account standard

parts such as rivets, nuts or bolts), that configure a set of complex interrelated systems.

- Aircrafts are build up in a sequential process, where parts are assembled into assemblies, airframes and major components. Each of them are usually designed and manufactured in different countries all over the world [Mas et al., 2014]. For example, the A400M model is produced in Belgium, France, Germany, Portugal, Spain, Turkey, and the U.K. among others. To coordinate this supply chain and assemble the airplanes on time it is necessary to deliver each part on the due date or an entire airplane could be delayed because one part is missing
- Aircraft are long life cycle products. One aircraft model can have a life cycle of more than 50 years. During this time, improvements and the development of new versions need to be handled with agility.

In the last years, the Aeronautical industry has not remained aside from Industry 4.0 revolution. As in other industries, globalization and digitization have become central features. In fact, the aeronautical industry has been ahead in the use of digital solutions. A wide range of product lifecycle management (PLM) tools have been deployed in the aeronautical industry and have resulted in highly digitized processes from aircraft design to aircraft maintenance [Mas et al., 2014]. This transformation began in the late 60's [Mas et al., 2015a] with the introduction of CAD systems for aircraft design and MRP systems. As time has past, there has been a major integration between the different software systems used (Computer Aided Applications (CAx), Product Lifecycle Management (PLM), Enterprise Resource Planning (ERP) and Manufacturing Execution Systems (MES) [Mas et al., 2019]. The aim of the industry is to be able to use them to manage not only the development and production process but also the whole product life cycle: from the development to the end of life [Ríos et al., 2016].

1.2 Motivation

In spite of the strong digitization that has happened recently in the aeronautical industry, planning and scheduling processes have consistently remained almost unaffected. Most of the activities that are related to these processes continue to use manual procedures that rely on the knowledge of experts.

Nevertheless, the digitization of scheduling processes is a must not only for MES systems implementation but also for Industry 4.0 deployment. In [Schläpfer et al., 2014] they include these three goals for Industry 4.0 which cannot be afforded without an improved planning and scheduling process:

- Higher flexibility through dynamic planning, control and execution.
- Higher productivity and resource efficiency for customized products.

- Shorter lead times through the application of intelligent analyses.

Scheduling problems have been widely studied since the early years of Operations Research. However, there is a low rate of digital scheduling solutions deployed in the industry. One of the reasons for this has been the lack of standard products and also the complexity of the problems.

In consequence, this thesis aims to close the gap between scheduling research and its implementation in real cases for the aeronautical industry. To begin with, I have analyzed the different planning and scheduling problems existing throughout its supply chain.

Four main planning and scheduling problem categories were identified during the analysis. Only one of them had been widely studied in the existing literature. Therefore, I have studied in detail the other three that, to the best of my knowledge, had not been addressed yet. For each of them, I have translated the business needs into requirements and made a model proposal. Moreover, experimentation has been performed with industrial use cases, solving the instances in times suitable for the real implementation in most cases.

The first models provided were deterministic. Thus, this work would have been insufficient if no uncertainty had been taken into account. In consequence, one additional part is dedicated to it.

In the last part, I share some conclusions on the data structure and exchanges that are necessary for the previous model implementation in the aeronautical industry.

The conclusions of this thesis will allow the digitization of the planning and scheduling processes and provide a more efficient and agile decision making process, directly related to an increase in productivity.

1.3 Objectives

Taking the industrial context into account and focusing on the challenges regarding planning and scheduling processes and tools, the following research questions arose:

- 1. What are the relevant planning and scheduling problems within the aeronautical industry?**

As stated before, although scheduling problems have been widely studied since the early years of Operations Research, examples of real application in the industry are rare.

One of the reasons for this can be the difficulty in matching the published solution methods from the literature with the real-industry problems.

Therefore, my first objective has been to identify and classify the relevant planning and scheduling problems within the aeronautical industry. For this classification, I had to decide the criteria to order the problems. I chose to use a two-axis classification. The first axis refers to the different steps in the aeronautical supply chain: from part manufacturing, to

airframe assembly and final assembly lines. The second axis stands for the time horizon: from mid-term to short-term scheduling.

2. From the relevant planning and scheduling problems, which of them have already been studied?

My next step was to perform a detailed literature review on applied articles dealing with planning and scheduling problems in the aeronautical industry. Those existing articles were classified using the two-axis framework resulting from the first step. As a result, the current knowledge gaps were clearly identified.

From the four main problems I had identified, one of them turned out to be widely addressed in the literature. The other three had only partially addressed or unattended.

3. How can the not-studied problems be addressed?

The objective at this step was to study in detail the three unattended problems. I followed a bottom-up approach for each problem.

First of all, a relevant case study from the aeronautical industry was selected. That case study was translated into problem requirements in a deep collaboration with the actual process owners in the industry. After, an in detail literature review was used to categorize the problem and identify the approaches used previously for similar problems. To end with, a model was developed for the problem and validated against real industrial instances.

4. What additional features should be taken into account to ensure the solutions provided are valid for an industrial deployment?

The objective of the thesis was not only to provide "academic" solutions but also to enable their implementation in the industry. Therefore, I have had to make sure that solution times are good enough but also that the used data can be easily available in the existing software eco-system PLM - ERP - MES.

1.4 Methodology

This thesis has been developed under the framework of Operations Research. This is, as defined by Lawrence et al [Lawrence and Pasternack, 2002], *"The discipline that adapts the scientific approach for problem solving to executive decision making in order to accomplish the goal of "doing the best you can with what you've got"*. Although this area of research has widened its limits to be defined as *"an approach to problem solving that employs quantitative analysis to help managers make decisions"* [Dennis, 1991], planning and scheduling problems remain among the core problems addressed by Operations Research.

Therefore, throughout the work I have gone through the major phases of an Operations Research project [Churchman et al., 1957]:

- **Problem selection and characterization:** In this case, this was one of the main steps. Enough time was invested in order to identify the planning and scheduling relevant problems in the aeronautical industry. Also, I had to work on the problem prioritization and their characterization with regards to the existing literature classification.
- **Formulating the problem:** At this stage, statements of objectives, constraints on solutions, appropriate assumptions, descriptions of processes, data requirements, alternatives for action and metrics for measuring progress have been introduced.
- **Constructing a mathematical model to represent the system under study:** I have identified the kind of problem to be addressed within the literature, together with the sort of model suitable for their representation. I have used both MILP formulations and discrete event simulations.
- **Solving the model:** For each of the models, I have selected the most adequate solving method. MILP models have been solved using AIMMS + CPLEX and MsExcel+OpenSolver. [Roelofs and Bisschop, 2011], [Mason, 2012]. The discrete event simulation model has been developed in Simio.[Simio LLC, 2017].
- **Testing the model and the solution derived from it:** Experimentation was performed using real industrial instances.
- **Establishing controls over solution:** Conclusions have been driven from the experimentation as for key instance features and their influence on the solution time, as well as future improvement opportunities.
- **Communicating:** The results from this thesis have had two main communication channels. On the one side, academical diffusion has been carried out by means of several articles and international conferences, which will be listed in section 1.6. On the other side, within Airbus, the results were shared with the process stakeholders. Whenever the resulting model was ready for go-live implementations, training and incidence solving channels were put in place.

1.5 Relevant Contributions

To begin with, this thesis provides an extensive review on the planning and scheduling problems from the aeronautical industry. They have been classified using a two axis representation (supply chain step and time frame). Moreover, an in depth literature review has been performed. The main knowledge gaps have been identified, using the presented two axis classification to sort the existing literature. I believe that this classification and knowledge gap analysis on its own is already of great interest for both academia and production managers. For production managers

because it builds a bridge between the problems in the industry and the existing research, enabling a fast identification of the existing solutions for each problems. For practitioners because it characterizes the problems in terms of the scheduling categories used in the literature and identifies research gaps that were still unexplored.

Afterwards, I have studied in detail three scheduling problems that had not been addressed yet. For each of them, I have translated the business needs into requirements. This has resulted on the description of new scheduling problems. Also, I have made a model proposal per problem. Moreover, experimentation has been performed with industrial use cases, solving the instances within times suitable for the real implementation in most cases.

The first models I provided were deterministic. Thus, this work would have been insufficient if uncertainty had not been taken into account. In consequence, one additional part is dedicated to it. In chapter 8 I have discussed different uncertainty approaches and selected two of them to be implemented. In chapter 9 a discrete event simulation is used to help a production manager to choose between different baseline schedules by comparing its performance when facing disruptions. Another approach is presented in chapter 10, where a model for re-scheduling was developed. These two models are real examples on how uncertainty can be incorporated in the scheduling decision making process. Furthermore, the rescheduling model together with the baseline scheduling model ensures production optimization from its start to the final product delivery.

In the last part, I share some conclusions on the data structure and exchanges that are necessary for the previous model implementation in the aeronautical industry. A flexible and fluent information flow between systems is crucial for Industry 4.0 implementation. Therefore, this data mapping is a must for a smooth implementation of any scheduling system within a real industrial environment. Moreover, it can be used as a baseline for a future planning and scheduling ontology definition.

1.6 Scientific Production

This work has resulted on 3 published articles (one in a Q1 journal, another two indexed in SCOPUS, Q2 and Q3), 2 book chapters and 8 international conferences, 3 of them with published proceedings. Figure 1.3 provides an overview of all this contributions. In that figure, there is a swim line for each of the Parts of this thesis, that will be explained in section . International conferences are represented using green symbols if the conference has published procedia and blue circles if not. Blue squares are used for book chapters and the light blue hexagon for articles.

It is also worth mentioning that part of this research is related to the results of HEFESTO project (High Efficient Factory basEd on complex conceptS in the digiTal mOckup). It is a FEDER funded research project, through the Spanish CDTI with an overall budget of 2.3 million euros, lead by Airbus, with CT and Idener as partners. I participated in it as leader of the line balancing

Figure 1.3: Relevant Contributions' Timeline

and scheduling activities.

Finally, as a output from this thesis, a collaboration with LAAS-CNRS has been established. Thanks to this collaboration, the Industrial Engineering and Logistics (ETSII-UPM) research group is now part of the ANR PER4MANCE project that addresses further issues on aeronautical scheduling problems, focusing on the final assembly line use case.

The complete list of publications and conferences is as follows:

Articles

- Borreguero, T., Pulido, R., García, A., & Ortega, M. (2017). Flexible Job Shop scheduling with operators in aeronautical manufacturing: A case study. *IEEE Access*, 6, 224-233. (JCR Q1, IF 2018= 4.098)
- Borreguero, T., Mas, F., Menéndez, J. L., & Barreda, M. A. (2016). Scheduling methodology for the aeronautical industry during production and industrialization phases. *Journal of Manufacturing Technology Research*, 8(3/4), 85-98. (SCOPUS Q3)
- Borreguero, T. (2017). Scheduling of an aeronautical final assembly line: a case study. *Procedia Manufacturing*, 13, 1167-1174. (SCOPUS Q2)

Book Chapters

- Pulido, R., Borreguero, T., García, A., & Ortega, M. (2017, July). Analysis of the robustness of production scheduling in aeronautical manufacturing using simulation: A case study. In *IFIP International Conference on Product Lifecycle Management* (pp. 174-183). Springer, Cham.

- Borreguero, T., García, A., & Ortega, M.(2014). A MILP Event Based Formulation for a real-world multimode RCSP with generalized temporal constraints. In *Managing Complexity* (pp. 113-120). Springer, Cham.

Proceedings of International Conferences

- Borreguero, T., Mas, F., Menéndez, J. L., & Barreda, M. A. (2015). Enhanced assembly line balancing and scheduling methodology for the aeronautical industry. *Procedia engineering*, 132, 990-997.
- Borreguero, T., García, A., & Ortega, M. (2015). Scheduling in the aeronautical industry using a mixed integer linear problem formulation. *Procedia engineering*, 132, 982-989.

Communications in International Conferences & Workshops

- Borreguero, T., Pulido, R., Ortega, M. & García, A. (2019) Production planning and scheduling in airframe manufacturing: a case study. 30th European Conference on Operational Research (EURO 2019). Dublin, 23-26 June 2019.
- Pulido, R., Borreguero, T., García, A. & Ortega, M. (2017) Analysis of the robustness of production scheduling in aeronautical manufacturing using simulation: a case study. IFIP International Conference on Product Lifecycle Management. Seville.
- Borreguero, T.(2017). Scheduling of an aeronautical final assembly line: a case study. Manufacturing Engineering Society International Conference. Vigo.
- Borreguero, T., Artigues,C., García, A., López, P. & Ortega, M.(2015) Multimode time-constrained scheduling problems with generalized temporal constraints and labor skills. Multidisciplinary International Conference on Scheduling: Theory and Applications Prague.
- Borreguero, T., Mas, F., Menéndez, J.L, & Barreda, M.A. (2015) Enhanced assembly line balancing and scheduling methodology for the aeronautical industry. Manufacturing Engineering Society International Conference. Barcelona.
- Borreguero, T., García, A. & Ortega, M (2015) Scheduling in the aeronautical industry using a mixed integer linear Pproblem formulation. Manufacturing Engineering Society International Conference. Barcelona.
- Borreguero, T., Ortega, M. & García, A..(2014) Multimode TCSP with generalized temporal constraints: a MILP formulation. 20th Conference of the International Federation of Operational Research Societies. Barcelona.
- Borreguero, T., Ortega, M. & García, A..(2013) A MILP Event Based Formulation for a real-world Multimode RCSP with generalized temporal constraints. International Conference on Industrial Engineering and Industrial Management. Valladolid. 10-12 July.

1.7 Document Structure

This document is divided in six parts. This first part is dedicated to the introduction and to the review of the planning and scheduling process in the aeronautical industry. It follows a literature review on aeronautical industry solved use cases and ends with the selection of the three problems to be addressed in the rest of the thesis.

Afterwards, Parts II to IV are dedicated to each of the three selected problems and Part V to ways of dealing with uncertainty. They follow a similar bottom-up approach. To begin with, the planning or scheduling problem is presented. To do so, I describe an specific use case of the aeronautical industry. Then, the problem is generalized and classified in terms of the existing problems in the literature. This is followed by a review of existing approaches to similar problems in other industries. In consequence, a modelling approach is selected, developed and tested using real data. Thanks to the experimentation results, final conclusions are retrieved for both the specific use case and the more general problem.

The problems that are addressed in each part are:

- Part II addresses the short term scheduling of airframe assembly lines.
- Part III reviews the mid term planning of airframe assembly lines.
- Part IV deals with the short term scheduling of final assembly line stations.
- Part V studies possible means of dealing with uncertainty.

After these, Part VI provides some hints on the data interfaces and structure needed for a real implementation of the former models. Integration of the planning and scheduling systems with the existing tool ecosystem needs is be taken into account.

To end with, final conclusions of this thesis are presented in Part VII.

SCHEDULING IN THE AERONAUTICAL INDUSTRY

2.1 The Aeronautical Supply Chain

The aeronautical supply chain is a complex ecosystem of different tiers of suppliers; original equipment manufacturers (OEMs); maintenance, repair and overhaul (MRO) providers; and customers, which include airlines and armed forces. The aeronautical industry has experienced a constant increase on sales during the last years. They need to provide more aircrafts but also more sophisticated ones. Last programs launched intend to increase operating efficiency by 15-20 % [Bernardini et al., 2013]. As an example, Figure 2.1 summarizes the advantages reported by Boeing manufacturers for its last development, the Boeing 787.

Another important feature of aeronautical supply chain is the long throughput time of their product manufacturing. From the time when an aircraft part is manufactured at a tier-3 supplier level to when it becomes part of the final aircraft and is delivered to the customer, it can take up to a few months to pass through different stages of the supply chain. Furthermore, the designing of a new aircraft model can take up to five years. As a result of this long throughput time, aeronautical companies have to decide between carrying large levels of inventory or being exposed to an increased risk of supply shortage. These can only be achieved with an increasing co-operation throughout the aeronautical supply chain. Original equipment manufacturers depend on their supplier network to meet the delivery schedule of their products and services. Moreover, they have focused on the most core activities and created network of tier 1 suppliers that, depending on the program, are even involved in design activities [Murman et al., 2000]. Figure 2.2 shows Boeing 787 Structure Suppliers map. In that image, we can see how the percentage of internal manufacturing has been strongly reduced from Boeing 737 share in the 1960s.

Figure 2.1: Improvements in Boeing's Last Development (787) [Boeing, 2019]

Along the supply chain, parts are integrated in small assemblies that are then used to build up major components. In a last step, major components are delivered to final assembly lines, where the aircraft is assembled and tests are performed. Figure 2.3 provides an example of this product breakdown structure for a small aircraft (Skyscar). [Caggiano et al., 2015]. Within this supply chain structure, three main steps can be distinguished:

- **Component manufacturing:** main component types are equipment, sheet metal parts and composite parts. They are delivered to all the three levels of the supply chain.
- **Airframe manufacturing:** Major components, such as wings or nose fuselage, are manufactured in separate lines and sent to final assembly lines. They can include the assembly of smaller components.
- **Final assembly lines:** They are in charge of the integration of major aircraft components and the overall aircraft testing.

In the next subsections, I will provide a more detailed description of each of those steps.

2.1.1 Component manufacturing

Forty years ago, aluminum dominated the aerospace industry. Due to its light weight and low price, it represented more than 70% of an aircraft in the 1980s. It was used everywhere from the fuselage to main engine components. Other new materials such as composites and alloys were also used, including titanium, graphite, and fiberglass, but only in very small quantities. This has changed. Nowadays, environs only 20% of an aircraft is built from aluminum. [Strandridge, 2014].

As an example, figure 2.4a shows the small number of parts that are build up in aluminium for Boeing 787. Most of the non-critical structural material (paneling and aesthetic interiors)

Figure 2.2: Boeing Supplier Structure for Boeing 787 Compared to that of 1960. [Ro, 2013]

now consist of even lighter-weight carbon fiber reinforced polymers and honeycomb materials, which are commonly referred to as composite parts. Boeing's 787 structure is now made at most of carbon laminate, as it can be seen in figure 2.4b.

Sheet metal parts manufacturing follow a standard Job Shop process. In most cases, this kind of parts are mainly bought to suppliers. In the contrary, composite materials are part of the strategic processes for aircraft manufacturers. They are subject of continuous research in order to improve their properties (for example, in terms of electrical protection) and their profitability [Mrazova, 2013], [Díaz and Rubio, 2003]. Also, their manufacturing has important constraints additional to that of sheet metal manufacturing: the raw material usually has short life cycle time and there are special processes that are not easily scheduled, such as the autoclave curing.

To end with, the development and manufacturing of equipments is more and more complex in recent aircrafts. However, this activities are deployed by equipment suppliers, out of the umbrella of aircraft manufacturers.

Figure 2.3: Product Breakdown Structure for Skyscar, a Small Aircraft, [Caggiano et al., 2015]

(a) Aluminium in 787

(b) Carbon laminate in 787

Figure 2.4: Comparison Between Aluminium and Carbon Fibre Parts for Boeing 787 [Boeing, 2019]

2.1.2 Airframe manufacturing

Major components are usually assembled in tier-1 suppliers or by the same OEMs. They are major parts of the aircraft, which are then delivered to the final assembly line. Their production usually includes the assembly of smaller components, structural assembly and some equipping also.

Their assembly tasks are more standard than the ones of final assembly lines, as those cover the aircraft furnishing which is the most customized part of the process. However, they may also have some customer dependent configuration. Moreover, that configuration changes will be more and more common due to the increase of customer customization options.

In most cases the same line produces components for a family of aircrafts, which results on a set of different final products sharing some of the resources in the line. For example, St Eloi plant in Toulouse manufactures pylons for most Airbus models. Also, the fan cowls for all the aircrafts of the same model share the assembly line even if they are significant differences between them depending on the engine model each aircraft has.

The production rate for a major component is strongly related to the takt of the final assembly line. In some cases, some stock can be used for components though. For example: central fuselage coming from Bremen to A400M FAL in Seville must be delivered with a JIT policy and inventory is not an option for it. Nevertheless, smaller airframes such as fan cowls or even wings can be stocked for some time if required.

Whenever inventory is an option, the airframe annual production plan can be calculated using aggregate production planning, and therefore different production rate changes can be used during the year. Also, that kind of approach is useful when different products are produced in the same assembly line, in order to reduce changeover times if relevant.

2.1.3 Final Assembly Lines

Final assembly lines are in charge of the integration of major aircraft components and the overall aircraft testing. Traditionally, aircrafts were built in parallel docks. These assembly lines have been transformed, in the case of most aircraft manufacturers, into takt paced assembly lines or moving lines. Boeing was the first commercial aircraft manufacturer to make this movement, beginning in 2002 with the transformation of 737 final assembly line to a moving line. They reported lead time reductions of more than 30% related to this assembly line transformation [Gastelum, 2002]. Most final assembly lines follow a similar structure. As an example, I will describe Airbus A350XWB final assembly line [Airbus, 2019b]:

- First stations are dedicated to fuselage assembly, including nose landing gear installation.
- Then, the wings and vertical and horizontal tails are attached to the fuselage, together with other minor assemblies such as engine pylons and landing gears. At the same time, the inside of the cabin is furnished up to some extent, including the installation of storage compartments, floors, carpets and sidewall panels and partitions.
- On a next station, ground tests are performed to validate all mechanical, avionic and electrical systems. Also, final refurbishing is done, both in the inside of the cabin (installing seats, as an example) and in the outside (closing belly fairing panels, landing gear doors and wing leading edges).
- A last station is dedicated to outdoor and flight line tests.

In terms of product standardization, while the structural assembly and ground tests have a high degree of commonality among different serial numbers, furnishing has a high variation ratio between products as it compromises the installation of most of the parts that are likely to be customized by the client.

It is also important to point out that final assembly lines are frequently dedicated to a family of aircrafts, instead to a single product. For example, Boeing 777 assembly line deals with

Figure 2.5: A320 FAL [Airbus, 2019b]

four different models 777 Freighter, 777-200 ER (Extended Range), 777-200 LR (Long Range) and a 777-300 ER [Fetters-Walp, 2010]. As for the other main commercial aircraft manufacturer, Airbus, he has eight final assembly lines: five identical ones covering A320 family (three in Europe, one in China and another in the USA), and another for each of the widebody model families A330, A350 XWB and A380.

2.2 Planning and Scheduling in the Aeronautical Supply Chain: Overview

Stadtler and Kilger, [Stadtler, 2011], in their book *Supply chain management and advanced planning* go through the different planning and scheduling processes that may exist within a supply chain . They use for their classification the Supply Chain Matrix, shown in figure 2.6. This matrix uses two dimensions to classify the planning and scheduling processes: the time horizon and the supply chain process. The time horizon is divided into short term, mid-term and long term. On the other side, the supply chain process refers to procurement, production, distribution and sales. This thesis is focused on the production processes.

Each time a new product is launched, decisions on the **long term** level must be taken. In the aeronautical supply chain, the supplier and partner selection is a key decision at that step. Tier-1 suppliers act more and more as risk sharing partners who take in charge the development from the design to the manufacturing of specific aircraft parts. Materials selection is also important at that stage. Some standard parts and raw material (for example, titanium) have long lead times and need estimations must be done early in the design phase.

Figure 2.6: Supply Chain Planning Matrix [Stadtler, 2011]

When a new program comes, new facilities are usually built or major changes made in existing ones. Also, the sharing of the sub-assemblies and the final assembly plant location must be decided. In most cases, this sharing is also led by historical and political issues. For instance, in military programs, offsets are frequently part of the contract. Part and subassembly transport between sides is usually done using special transport aircrafts. Nevertheless, some special cases may happen. For example, for the A380 wings transport from the UK to Toulouse, a dedicated road was built from Bourdeaux' s port to the final assembly line in Toulouse.

Due to the long lead time of aeronautical programs, other long term decisions happen within the life of a product. That is the case of the opening of new production sites. For example, Airbus A320 family has recently opened two new FALs in China and the USA as part of a strategic decision to increase sales in those areas. Also, they can be changes on the suppliers during the program life. Moreover, the production systems must be defined in the long term. Aircraft final assembly lines are mainly designed as pulse lines or even moving lines. The number of stations on an assembly line is defined during the early stages of an aircraft program. Normally, that decision is strongly linked to technological issues and rarely changed during the program life cycle but in case of overall re-engineering. This decision leads to major investments on specific jigs and tools.

The initial allocation of tasks to a station is defined at this early stage. Once a first allocation is done, the capacity of the line is tested, taking into account the changes of rate during the product ramp up. Once the line is running, bottlenecks are analyzed and some tasks may be changed to less loaded stations. However, there is usually enough flexibility in the line to adapt it to the required set of cycle times.

As for **mid term** decisions, Stadtler and Kilger classify them in capacity planning and master production scheduling. Production orders for aircrafts are set up within this time frame. Once production orders are fixed, there is a need to allocate the production to the different production sites. For example, choose the final assembly line and the suppliers for each of the units to be manufactured.

In terms of the production system, more details on the operation mode of the plants must be decided. The production rate in the different production sites must be calculated. Usually, it changes once per year. They are calculated taking into account the yearly hour availability and the number of units to be delivered to the client: *Takt time = Yearly hour availability / number of units*.

As a result, in synchronized pulse lines, some of the task allocation to the stations may have to be reviewed. In mixed model assembly lines, the takt time may be variable through the year, to cope with the different product demands. In that case, the period for each takt time must be decided.

Capacity planning must also be done at that stage. The aeronautical industry remains intensive in human labour, so having the adequate human resources is a must. Resources must be distributed within the plants to the different lines and stations. If necessary, subcontracting must be studied.

Finally, **short term** decisions are related to the daily operation of the supply chain. As at this stage the production plan is already set, these decisions affect isolated production sites.

The detailed shop floor schedule is done at this stage. That process is different depending on the production step. Part manufacturing plants usually follow a Job Shop organization, so they must take decisions about machine and resource allocation and lot sizing. As for final assembly lines, they follow a flow line with fixed lay out. It has to be decided if they follow a fixed or variable takt time and if they will allow travelling work from one station to the other. Also, they must decide if they will follow a synchronized operation mode. At the same time, stations within those lines may handle hundreds of tasks. In consequence, the detailed scheduling of a station is an important resource constraint scheduling problem to be solved.

Airframe manufacturing is somewhere in between part manufacturing and final assembly lines. Some of them are organized in pulse lines, similar to those of final assembly lines. In other cases, several airframes share the same resources, jigs and tools and therefore its detail scheduling is more similar to Job Shop scheduling problems.

2.3 Planning and Scheduling in the Aeronautical Supply Chain: Theoretical Classification

The problems explained in the previous section can be classified into major planning and scheduling problems from the literature.

The mid term planning for parts and airframe manufacturing can be classified within **Aggregate Production Planning** (APP) problems. These problems were defined in 1972 by Buffa and Taubert [Buffa and Miller, 1979].

For final assembly lines, the mid-long term planning problems are included within **Assembly Line Balancing Problems** (ALBP). These problems have been widely studied, being the most relevant studies those from Salveson [Salveson, 1955], Baybars [Baybars, 1986] and Boysen [Boysen et al., 2007].

As for short term scheduling, most of the part manufacturing problems are very similar to those on other industries. Sheet metal parts, for example, have been widely studied. However, composite parts have some specific constraints that are less frequently referred to in the literature, such as the limited life time of the raw material and the use of autoclaves. They are all included within **Machine Scheduling Problems** (MSP), which were classified by Blazewicz in 1986 [Blazewicz, 1986].

Going downstream in the product life-cycle, the short term scheduling for airframe manufacturing depends on the shop floor organization. For smaller components, there are mixed model assembly lines, where the scheduling problem is once again part of **Machine Scheduling Problems** (MSP). However, the aeronautical industry remains intensive in manpower. For that reason, the human resource allocation is as important as the machine allocation. Machine scheduling problems with operators are not frequent in the literature.

Bigger components are assembled in takt paces production lines. In such cases, short term task scheduling is similar to the one of final assembly lines. The objective is to assign resources (mainly human, but also jigs and tools) to the tasks, that must be accomplished within a time cycle and complying with restrictions between them. These problems have been classified in 1999 by Brucker [Brucker et al., 1999] and are known as **Resource Constraint Scheduling Problems** (RCSP). This kind of problems are mainly applied to project scheduling, where the number of tasks is within the range of hundreds. Nevertheless, in the aeronautical industry it is frequent to have real instances of more than a thousand tasks.

These four problems have been allocated in what I will from now on call the *Aeronautical Supply Chain Planning and Scheduling Matrix*, presented in Figure 2.7. In that matrix, the x-axis refers to the production step and the y-axis to the time frame.

2.4 Planning and Scheduling in the Aeronautical Supply Chain: Literature Review

In this section, I will present a review on the existing literature on planning and scheduling problems applied to the aeronautical industry. To do so, I have searched for use cases and articles that deal with real applications on any step of the aeronautical supply chain. A total number of 15 references have been identified. The articles are presented using the classification from

Figure 2.7: Aeronautical Supply Chain Planning and Scheduling Matrix

previous section and the *Aeronautical Supply Chain Planning and Scheduling Matrix*.

2.4.1 Assembly Line Balancing Problems

By far, assembly line balancing is the area where more references have been identified.

Rios et al [Ríos et al., 2012] and Pralet [Pralet et al., 2018] focus on the industrialization phase, that is, the first definition of the line and the re-definition caused by later product modifications. Rios et al reported in 2012 an heuristic method to support the validation of assembly line balancing in the development phase. Given a set of tasks, their allocation to stations and a product delivery rate, they looked for a set of feasible schedules per station and they evaluated them against a set of indicators. To do so, they developed an heuristic based on a ranked position weight method. For each task, they provided a speciality, a range of operators and an aircraft area. Space constraints and precedence constraints between tasks were taken into account. As this heuristic was developed for the development phase of the aircraft, its aim was to validate an scenario and not to provide a detailed feasible solution to the shopfloor, as at the development phase the information is not mature enough to create a real production schedule.

Later, Pralet et al [Pralet et al., 2018] developed an heuristic method to evaluate the impact of design changes on an existing line balancing. It takes into account only direct precedence constraints between tasks and zone saturation. Operators are not taken into account and the whole problem is tackled with a high level approach.

Another set of works are related to the operation of the line during the production phase. To begin with, Heike [Heike et al., 2001] dealt with a flow line production model for an aircraft

fuselage joint. He presented a line with seven assembly stations, each of them with capacity for two aircrafts at a time. He used three models to evaluate the difference between operation policies: using variable cycle and random cycle times against the most common use of constant cycle times per aircraft. Another model is used to evaluate the usage of flexible crew, that could be shifted to an eventually overloaded station. To do so, he modelled the work at a station as a single job, with a certain amount of resources usage.

Biele and Mönch [Biele and Mönch, 2015] dealt with a problem similar to Heike's. They modelled a flow line where each aircraft has a certain workload in each of the stations and there is a fixed aircraft sequence. First, they used a variable neighborhood search (VNS) approach to assign to each station a number of workers and processing times for each jobs. Then, they built a simulation model based on the simulation framework proposed by Ziarnetzky et al [Ziarnetzky et al., 2014] to evaluate the performance of the deterministic schedules under uncertainty. By means of the simulation, the trade off between stop and fix and travelling work strategies was analysed.

They made a further extension of the deterministic model in 2018 [Biele and Mönch, 2018]. There, the authors compared two different mathematical models for the fuselage assembly line. The first formulation was a time-indexed linear formulation that allows for a flexible allocation of workers to periods and stations while the second one had a non-linear objective function and allowed only a fixed assignment of workers to stations. Both were solved using matheuristics. After testing randomly generated and real instances they concluded that flexible worker allocation and variable flow times are more efficient than fixed scenarios in low volume scenarios as is the case of the aeronautical industry.

Moreover, in [Biele and Mönch, 2019], they studied also the sequencing problem. They presented a manufacturing system consisting of two subsystems: the first one with parallel mixed-model assembly lines and a second one with identical parallel stations. The model dealt simultaneously with: aircraft allocation to lines, aircraft sequencing within the line and start-end dates per station.

2.4.2 Resource Constraint Scheduling Problems

In 1994, Scott [Scott, 1994] published a seminal study on how to model aircrafts assembly lines. He introduced the major issues that characterise aircraft assembly line stations. That is:

- The aircraft assembly line is modelled as a set of parallel and in series stations. Within each station, different jobs need to be done. Those jobs are related each other with precedence relationships.
- Space constraints must be taken into account, as some small areas within an aircraft may gather a high number of tasks. That is frequently the case of the cockpit or avionics bay areas.

- Crew movement is another fact that must be addressed. Operators do not have a fixed position and may move from one part to the aircraft to another during a shift. Nevertheless, that can be a source of inefficiency.
- Each job must be assigned a number of crew members. A given task may admit different numbers of members.
- Learning curves: they had been defined by Wright in 1936 [Wright, 1936] as a means calculating the evolution of assembly time during the ramp up phase of an aircraft model.
- Resource constraints different from crew members, such as cranes and tools.
- Reworks and rejection rates that may lead to unexpected inflows during production.

However, no reference on how to schedule the tasks within a station were found at the beginning of this thesis in 2013. Only general articles about this genre of problems had been published. The most recent had been written by Koné et al in 2011 [Koné et al., 2011]. He made a benchmark of different MILP formulations for the problem and suggested a new Event-Based formulation which overran the prior studies. He used standard instances from PSPLIB [Kolisch and Sprecher, 1997]. None of those instances cover all the complexity needed to model a takt paced aeronautical assembly station.

It is important to point out that during the writing of this thesis, several related works have been published. This proves the interest and relevance of the subject.

In 2015, Silva et al [Silva and Morabito, 2015] presented a study where they compared the cost of different station lead times and the impact of considering single or multiple skills within an operation. However, they only took into account precedence constraints (no time lags) and one mode execution per task. Moreover, their case study was applied to a 25 task instance.

A combination of Line Balancing and detailed scheduling was suggested by Vrba et al [Vrba et al., 2015]. They used a multi-agent approach where single agents schedule each station and then cooperate for the allocation of outstanding work in the next stations. Nevertheless, they model the station jobs in low level of detail: no multiple modes are studied and only strict precedence constraints are taken into account.

Martigniano, Battaia and Battini [Martignago et al., 2017] dealt with the joint problem of scheduling and operator assignment for tasks in an aeronautical assembly station. They used a cost-oriented objective function to choose between different operator skill scenarios and solved the model for an industrial 80 task instance. Precedence and non-parallel constraints were taken into account. However, they do not include multiple modes in terms of skills or number of operators.

In 2018, Arkhipov et al [Arkhipov et al., 2018] presented a use case based on the scheduling of tasks within a station, subject to precedence and resource constraints (human and non-human renewable resources). They included also ergonomic constraints: an operator can only handle a

set of tasks up to a certain ergonomic limit. They applied it to real industry cases of more than 250 tasks. This is the closer use case to that of this thesis. Nevertheless, they did not take into account multiple-modes nor non-parallel constraints.

2.4.3 Aggregate Production Planning Problems

No references were found for this type of problems in the aeronautical industry. Nevertheless, aggregate production planning was defined by Mula [Mula et al., 2006] as one of the seven major production planning categories. Recent studies in this field have been published, focused on other industries, as is shown in Cheraghalikhanian's [Cheraghalikhani et al., 2019] literature review in 2019 . Therefore, this is a clear research gap for the aeronautical industry.

2.4.4 Machine Scheduling Problems

As it was explained before, this group of problems covers from part manufacturing (sheet metal and composite) to small airframe assembly. Four references were found. Three of them dealt with sheet metal parts manufacturing. The earliest one, by Esquirol et al [Esquirol et al., 1997] dealt with a sheet metal part cutting facility. They suggested the need to use a cooperative approach where a model provides a set of solutions that are then validated or modified including additional constraints by the user. Their idea of cooperation is relevant for other aeronautical supply chain steps as it is usually difficult to model all the constraints in a first approach. Jensen [B. Jensen, 2014] implemented a MILP model for parts scheduling and considered workforce constraints and limited space availability . Finally, Huag [C. K. Huang, 2006] used simulation to compare a Job Shop layout to a cellular manufacturing facility.

More recently, Da Silva studied in detail a scheduling problem in a mixed model assembly line for small assemblies [Da Silva et al., 2014]. He dealt with the scheduling of the manufacturing of eight parts that use adjacent features leading to non-parallel constraints between some parts. Also, he considered the same problem during different project stages. In a first stage, no worker constraints are taken into account: only makespan reduction. Then, parts must be delivered on time but the objective is to minimize the resource usage. He investigated different scenarios, depending on the workers' skills, trying to minimize the number of operators in each scenario. Although this article deals with a problem more complex than sheet metal parts manufacturing, it is still an example of a very simple assembly.

All these references are sum up in Table 2.1. Moreover, in Figure 2.8 they are displayed within the *Aeronautical Supply Chain Planning and Scheduling Matrix* presented in the previous section.

2.5 Conclusions & Problem Selection

The following conclusions are drawn from the literature review:

Figure 2.8: Literature Review Classified in the Aeronautical Supply Chain Planning and Scheduling Matrix

- The airframe area is the less studied one, both on the mid term and in the short term.
- In the short term, airframe scheduling belongs to **Machine Scheduling Problems**. Three of the four references found in that area are dedicated to sheet metal parts and one to small assemblies. There are important features in this area that have not yet been investigated. For example, there is no reference to composite manufacturing. This is a special case because specific constraints on raw materials limited life time and autoclave curing process need to be taken into account.

As for airframe assembly, it is usual to have a shop floor with shared resources between different assemblies, rather than only dedicated features, as in the problem presented by Da Silva [Da Silva et al., 2014].

- No references were found for **Aggregate Production Planning Problems**. Nonetheless, it is a relevant subject as recent researches have been dedicated to this area in other industries. This is a clear research gap for the aeronautical industry.
- The **Resource Constraint Scheduling Problem** had no published works at the beginning of this thesis in 2013. Also, it must be stated that each the works that were afterwards published, differ on the problem characteristics they take into account. Some of them deal with multiple modes per tasks and another with single modes. Also, the genre of constraints taken into account varies from only precedence constraints, to including also maximal and minimal time lags or non-parallel constraints. Finally, one reference takes into account

Table 2.1: Aeronautical Planning and Scheduling Literature Review Summary

No.	Ref.	Title	Problem
1	[Ríos et al., 2012]	A review of the A400M final assembly line balancing methodology	ALBP
2	[Pralet et al., 2018]	A scheduling tool for bridging the gap between aircraft design and aircraft Manufacturing	ALBP
3	[Heike et al., 2001]	Mixed model assembly alternatives for low-volume manufacturing: the case of the aerospace industry	ALBP
4	[Biele and Mönch, 2015]	Using simulation to improve planning decisions in mixed model assembly lines	ALBP
5	[Biele and Mönch, 2019]	Decomposition methods for cost and tardiness reduction in aircraft manufacturing flow lines	ALBP
6	[Biele and Mönch, 2018]	Hybrid approaches to optimize mixed-model assembly lines in low-volume manufacturing	ALBP
7	[Scott, 1994]	Modelling Aircraft Assembly Operations	RCSP
8	[Silva and Morabito, 2015]	Planning of an aeronautical structural assembly of jets using project scheduling approach with constrained resources and multiple modes	RCSP
9	[Vrba et al., 2015]	Agent-Based Production Scheduling for Aircraft Manufacturing Ramp-up	RCSP
10	[Martignago et al., 2017]	Workforce management in manual assembly lines of large products: a case study	RCSP
11	[Arkhipov et al., 2018]	Operator assignment problem in aircraft assembly lines: a new planning approach taking into account economic and ergonomic constraints	RCSP
12	[Esquirol et al., 1997]	Constraint-Oriented Cooperative Scheduling for Aircraft Manufacturing	MSP
13	[Da Silva et al., 2014]	Production scheduling of assembly fixtures in the aeronautical industry	MSP
14	[B. Jensen, 2014]	Production scheduling of assembly fixtures in the aeronautical industry	MSP
15	[Huang et al., 2006]	Simulation and analysis for layout of aerospace sheet metal process with lean concept	MSP

ALBP: Assembly Line Balancing Problems; **RCSP**: Resource Constraint Scheduling Problems;
MSP: Machine Scheduling Problems

ergonomy as a relevant scheduling parameter. This different approaches have been sum up in Table 2.2.

- The **Assembly Line Balancing Problem** is the most studied of the four. Eight references out of fifteen are dedicated to it. Also, Biele et al extended the initial work from Heike [Heike et al., 2001] to most of the relevant use cases in [Biele and Mönch, 2018], [Biele and Mönch, 2015], [Biele and Mönch, 2019].

Taking all these facts into account, I decided to tackle in the first case the airframe short term scheduling problem, focusing on a Job Shop with shared resources use case. Also, some

Table 2.2: RCSP Applied Review Summary

No.	Reference	Multiple Modes	Prec. Const.	Max and Min time Lags	Non-Parallel Const.	Method	Others
8	[Silva and Morabito, 2015]	No	✓	No	No	MILP	
9	[Vrba et al., 2015]	No	✓	No	No	CP	
10	[Martignago et al., 2017]	No	✓	✓	No	MILP	
11	[Arkhipov et al., 2018]	No	✓	✓	No	CP & ILP	Ergonomy

effort was dedicated to the definition of the main features from composite manufacturing, which make them different from sheet metal parts. Both of this problems will be presented in Part II.

Aggregate Production Planning seems to be a problem easier enough to be efficiently solved based on expert knowledge. However, having deployed an efficient short term model, it was demonstrated that the Aggregate Production Planning process can benefit from it following a related approach. This will be explained thoroughly in Part III.

As for final assembly lines and other takt paced production sides, the Resource Constraint Scheduling Problems had not been studied at the beginning of this thesis. Therefore, I studied it in more detail and the results will be presented in Part IV.

To end with, the Assembly Line Balancing problem has extensively being studied in the literature. At the same time, this problem is less important during the industrialization phase but less relevant as series production starts, because from then on only small changes are usually made. Therefore, it has been decided not to deal with this problem.

In a first approach, all the selected problems were studied from a deterministic point of view. However, due to the complexity of aeronautical products, delays and inflows are a daily issue. They can be caused by material shortage or resource availability, but also because of disruptions generated by defects and other inflows originated during production such as late modifications or new client requirements. Not taking uncertainty into account would have been ignoring a significant part of reality. In consequence, PartV is dedicated to two different uncertainty management strategies. They have been applied to the short term airframe manufacturing problem, but the approach could be extended to the other problems.

Part II

Airframe Manufacturing Short Term Scheduling: Machine Scheduling Problems

In this section I will focus on Machine Scheduling Problems in the context of the aeronautical industry. Figure II.2 shows this area within the Aeronautical Planning and Scheduling Matrix presented in Section 2.3. As it was seen in the literature review in Chapter 2, this applies to both parts and airframe manufacturing. In this area, the only references found were related to part manufacturing. Therefore, now I will focus on an airframe manufacturing use case.

Figure II.2: Aeronautical Planning and Scheduling Matrix - MSP

The structure of this part is as follows. To begin with I will present in detail a real industry use case. It describes a mixed model airframe assembly line in a Spanish aircraft manufacturer. This real use case is used to compile a list of requirements for the scheduling model, that are summarized at the end of Section 3.1.

Afterwards, Section 3.2 compares the problem from the use case to more general problems from the literature. The use case problem is classified within the existing categories for Machine Scheduling Problems. Also, solution methods already used for similar problems are reviewed.

Following the literature review, I have chosen to develop a MILP model for the airframe assembly line detailed scheduling problem from the case study (see Section 3.3). Although the model is made to fit the specific requirements from the use case, it has also been formulated so that it can be applied to other airframe assembly lines. Real industrial data have been used for

the experimentation, whose results are discussed in Section 3.4.

Finally, conclusions and further research directions are presented in Section 3.5. Within the conclusions, I have included some insights on how this model could be extended to the part manufacturing case.

AIRFRAME MANUFACTURING SHORT-TERM SCHEDULING

3.1 Problem Description

Airframes are major components of the aircraft. They are assembled in separated lines and then delivered to the final assembly line for the complete aircraft integration. As an example, Figure 3.1 shows pictures of three airframes: a Fan Cowl, an Horizontal Tail Plane (HTP) and a Nose Fuselage.

Airframe assembly lines are generally dedicated to a single airframe type but they are able to concurrently produce multiple aircraft models; therefore, this manufacturing process may be considered a mixed model assembly line. Per airframe, several jobs must be performed using a set of the existing machines. Human resources are a major asset of these production sites because the assembly is labour intensive. Managers should determine a production schedule and assign machines and resources (mainly workers) for each element. The main objective of these managers is to reduce costs while ensuring on time delivery.

There are some other important features of aeronautical production that is worth mentioning. To begin with, the cycle time is in the range of days or weeks, which is long compared to other series production industries, such as the automotive. Also, the majority of the processes rely on a significant manual workload. For this reason, the number of workers is a relevant cost contributor. Non-finished goods are another important cost contributor because each airframe could cost several thousand euros and the number of parts required for each system could be in the range of tens to hundreds.

As it was reviewed in Chapter 2, the production planning and scheduling for airframe assembly lines follows several steps. First of all, an aggregated planning is made yearly, to make sure the overall capacity is enough for the demand. Afterwards, a more detailed production plan

(a) Fan Cowl

(b) Horizontal Tail Plane (HTP)

(c) Nose Fuselage

Figure 3.1: Three Examples of Airframes: Fan Cowls, Horizontal Tail Plane and a Nose Fuselage

is generated. At that step, the production rates for each time period are set. For example, if during a year (with an estimated length of 202 working days) 42 units of each product must be delivered, that can be split into 100 days delivering 1 product each 4 days and 102 days delivering 1 product each 6 days. The decision making process to choose the production rate per period will be thoroughly studied in Part III. Now, I will focus on the short term scheduling that needs to be built once a production rate per product has been decided.

I will describe more in detail the airframe assembly line that has been chosen as case study. It is a real assembly line from an Spanish aeronautical plant. In this line, multiple product variants are assembled, using non-dedicated machines. Depending of the setup of the line, it can handle a variety of production rates. That production rates depend on the setup of some stations and the number of workers in each shift.

Two airframe units, a left hand side and a right hand side, are delivered for each aircraft. Also, the assembly line produces airframes for two aircraft models. In all, 4 airframes are produced on the line, called: Model-A LH, Model-A RH, Model-B LH and Model-B RH. A and B stand for two aircraft models and LH and RH for the right hand side and left hand side airframe. The name of the airframe is not revealed for confidentiality reasons.

The shop floor is arranged as a job shop with different assembly stations. There are six assembly stations or cells (A, B, C, D and F). In each cell, there are a set of machines. Each machine can be used for a subset of airframe models. During production, an airframe must proceed through nine processes, named using numbers: process 1, process 2 ... to process 9.

Figure 3.2 presents the assembly line layout and the path that is followed by an airframe during its production. The process number is identified by a circled number in the figure. The process is not totally linear. Process 1 is done in cell C. Then, process 2 goes to cell A and from then on, the airframe follows a linear path from cells A to F. In some cases, such as in cell B, two processes are executed in the same cell (processes 3 and 4). There are five buffers that exist between different processes. In Figure 3.2, the buffers are represented by the triangles. Although extra buffer spaces could be allocated, production managers explained they try to avoid this for safety reasons and a high risk of damage.

When scheduling, precedence constraints exist between the processes. In certain cases, the time lag between a process and its successor has a minimum or maximum value. For certain processes, there cannot be pre-emption.

A process requires the use of operators and machines. Operators' profiles vary depending on their qualifications. Each process can be performed using a subset of operator profiles. The number of operators working simultaneously on a process has an upper limit. To be complete, a process requires a fixed number of operator hours. The process is finished when the sum of the time each operator has invested in the process is equal to the process' workload, e.g., for an 8 hour process, I could assign 2 operators to work 4 hours or 1 operator to work 8 hours.

Two types of operator profiles are used in the assembly line: production and non-production.

Figure 3.2: Plant Layout

The first operators are paid when they are hired. If hired, they must be paid 8 hours per day even if they work less. The number of production operators per shift must be uniform during the scheduling horizon. Therefore, the production operator's cost is directly proportional to the maximum number of operators that are used for each shift. Non-production operator profiles are only paid for their effective working hours. Their cost is related to the workload of the processes they are assigned to.

The assembly line involves several types of machines, as shown in figure 3.2. Each machine is used for a subset of processes and airframe models. Set-up costs are either irrelevant or too high to be considered as a possibility during serial production. A machine can only be used by one airframe at a time. Certain machines maintain their own calendar and can only be used during certain shifts. Other processes do not require the use of a machine. Table 3.1 provides the information on what machines can be used per process and airframe. In that table, the assembly station or cell is listed in the first column, the types of machines in the second one, the quantity available is in the third column, the airframes that can use the machines in the fourth column, and the processes for which the machines are used in the final column.

Given a fixed production rate per product, the detailed scheduling must provide an allocation of machines and operators per airframe and time period to ensure all airframes are delivered in time.

To do so, I have pursued to schedule the lowest possible time horizon and repeat that schedule as many times as necessary. That lowest possible time horizon is calculated as the lowest common

Table 3.1: Machine Usage Per Process and Airframe Model

Cell	Machine	Qty	Airframe	Process
A	Machine A	1	All	Process 2
B	Machine B	4	All	Process 3, Process 4
C	Machine C-1	1	Model-A LH	Process 1, Process 5
C	Machine C-2	1	Model-A RH	Process 1, Process 5
C	Machine C-3	1	Model-B LH	Process 1, Process 5
C	Machine C-4	1	Model-B RH	Process 1, Process 5
D	Machine D-LH	2	Model-A LH; Model-B LH	Process 6
D	Machine D-RH	2	Model-A RH; Model-B RH	Process 6
E	Machine e	2	All	Process 7
F	Machine f	1	All	Process 8
	No Machine	4	All	Process 9

multiple (LCM) of the airframes cycle times (where the cycle time is the inverse of the production rate). For example, if Model-A has a production rate of 1 unit each 5 days and Model-B has a production rate of 1 unit each 2 days; the planning period will be 10 days (LCM of 5 and 2) during which we will produce 2 units of Model-A (one each for 5 days) and 5 units of Model-B (one each for 2 days).

To be finished, an airframe must go through the nine processes described before. Therefore, the schedule must include as many repetitions of a process as airframes need to be delivered. In the previous example, each process of Model-A must be scheduled twice and each process on Model-B must be scheduled 5 times. Where there are intermediate buffers, the processes need not be scheduled in order (process 3 can be performed before process 2 using an airframe from the buffer).

The objective is to generate a schedule for the time horizon that minimizes the inventory cost or the number of production operators that are needed. This schedule is divided into time slots and should assign an execution date for each operation, the number of operators and the machine to be used.

In summary, the scheduling of this airframe assembly line must fulfil the following requirements:

Units to be produced, cycle time and scheduling horizon:

- Each airframe model must be delivered with a cycle time equal to the demand Takt Time.
- During the cycle time of an airframe one unit of each of its processes must be scheduled .
- The scheduling horizon will be the LCM of all the cycle times.

- During the scheduling horizon, the number of airframes per model to be produced is equal to the scheduling horizon divided by the airframe cycle time.

Process characteristics and requirements:

- Each process needs to be performed in the corresponding jig.
- A process is only finished if it has had assigned enough operators through its scheduled period to fulfil the process workload.
- There is a range of possible number of operators to be assigned to each process.
- Some processes cannot be interrupted once started.
- Processes must be performed in a given order for each airframe.
- There are buffer positions only between some processes.

Jigs:

- Each jig can only process an airframe at a time.
- Jigs are set up at the beginning of the scheduling period. No configuration changes are allowed during the scheduling period.

Operators:

- Operators can only be assigned to a process at a time.
- The maximum number of operators needed in each shift (early, late) must be minimized.
- There are no operators during the night shift.

Until now this schedule had been calculated manually and relied on experts' knowledge. However, scheduling without the use of an automated system is time consuming, has a high probability of error and does take into consideration inventory costs.

3.2 Literature Review

As it was stated in Section 2.4, to the best of my knowledge, no study had previously addressed this problem applied to the aeronautical industry.

In the general literature, this belongs to machine scheduling problems. Those problems have been the subject of continuing research since the early days of operations research. This type of problem are NP-hard and in practice, are among the most intractable and classical problems.

The classical Job Shop Problem (JSP) refers to the scheduling of a set of jobs, J , (each job is divided into n operations) on a set of m machines with the objective of minimizing a certain

criterion and is subject to the constraint that each job has a specified processing order through all machines, which are fixed and known in advance [Zhang et al., 2009].

Blazewicz [Blazewicz, 1986] provided a classification of job scheduling problems and a survey study in 1983. More recently, in 1996 he updated the survey for the specific case of job shop scheduling [Balacewicz et al., 1996].

This problems are usually categorized using the general three tuple classification scheme $|\alpha|\beta|\gamma$ based on [Graham et al., 1979] where α indicates the the machine environment, β denotes certain job characteristics, and γ specifies the optimality criterion. According to that classification, this problem can be described as $J, 16 \mid pmtn, res, prec, r_j, ^\circ, ^\circ \mid \sum num_{operators}, buffer$.

- $\alpha = J, 16$. As machines are organized in a Job Shop mode, where each Job can be processed in a given set of machines and there is no fixed order between the orders coming from different jobs, then $\alpha_1 = J$. Moreover, $\alpha_2 = 16$ because 16 is the size of the machine set, as described in the previous section.
- $\beta = pmtn, res, prec, r_j, ^\circ, ^\circ$. $\beta_1 = pmtn$ because preemption can be an option for some of the tasks. $\beta_2 = res$: Resources are an important feature for this problem. They are two sets of renewable resources: machines and operators. $\beta_3 = prec$: The precedence diagram is an acyclic arbitrary graph. $\beta_4 = r_j$: although in most cases the release date for a job will be 0, there may be some cases where there is a specific release date for a job. $\beta_5 = \beta_6 = ^\circ$ as no upper bounds for the machine usage or processing times are specified.
- $\gamma = \sum num_{operators}, buffer$. The objective functions differ from the most common ones. I will look into two different functions: the operator cost minimization (which results on number of operators minimization) and the buffer size minimization.

On top of this general classification, the airframe assembly line scheduling problem in this section incorporates additional features that must be highlighted. First, it is a *Flexible Job Shop scheduling problem* as certain jobs may be performed by using more than one machine. In addition, *human resource* requirements must be considered. Each job requires the presence of an operator at each machine and the duration of the job on each machine depends on the number of assigned operators (which may vary within an interval).

In all, it could be classified as a *Flexible Job Shop problem with operators*. Three assignments must be solved concurrently; each job must be assigned to a machine, a time period and order and finally, to a number of operators per profile and active period. To our knowledge, this problem has not been previously addressed; however, its primary features have been separately analyzed.

3.2.1 Flexible Job Shop Scheduling Problems

Flexible Job Shop Scheduling Problems (FJSP) differ to classical Job Shop Scheduling problems in the fact that each operation can be done in a set of existing machines. They are being used

more frequently because flexible manufacturing systems are more effective when it comes to providing answers to a more complex and dynamic market.

In this problems, two assignments must be made to build a solution: the assignment of tasks to a machine and the scheduling of the tasks. In consequence it is a more hard problem than the classical Job Shop Scheduling problem.

Brucker and Schlie [Brucker and Schlie, 1990] were among the first to address this problem. In 2015, Chaudhrya and Khanb provided an extensive review of the state of the art for Flexible Job Shop Scheduling problems ([Chaudhry and Khan, 2016]). They reviewed 191 articles published between 1990 and 2014. The article distribution reveals the growing interest in this problem, as 150 out of 197 were published from 2010 onwards.

Nevertheless, most of the works presented (93.72 %) deal with the simple FJSP. The other 6.28% address real-world industrial applications, including topics such as setup and transportation times, maintenance, job/machine ready times, fuzzy/uncertain processing times, machine breakdown, job/machine ready times. There are no references related to simultaneous machine and personnel scheduling.

As for the solving techniques, more than 50% use hybrid methods or evolutionary algorithms. Moreover, most of the hybrid methods use also evolutionary algorithms. Therefore, evolutionary algorithms are the most common technique. The most cited articles in this field are those of Pezzella et al. [Pezzella et al., 2008], Kim et al [Kim et al., 2003] and Zhang and Gen [Zhang and Gen, 2005].

Although it is far from being as popular as Genetic Algorithms, linear programming was the fifth method in percentage (5%). As I will present a MILP model for the short term airframe assembly line scheduling presented problem, I will now focus on the existing MILP formulations for the FJSP.

3.2.1.1 MILP Formulations for the Flexible Job Shop Scheduling Problem

Demir [Demir and İşleyen, 2013] performed a survey on different mathematical models for the Flexible Job Shop Scheduling problem. All of them follow a common strategy for the machine assignment problem. Therefore, their classification is inherited from the general Job Shop Scheduling problem. MILP formulations for job shop scheduling problems were classified by Ku and Beck ([Ku and Beck, 2016]) into: disjunctive or precedence based models, time-indexed and rank-based or sequence position models.

There are some common notations for all the formulations. They use a set of n jobs to be performed in m machines. Each job has J_i operations, where O_{ij} is the i -th operation of job j . Parameters a_{kij} describe the subset of machines M_{ij} where operation O_{ij} can be performed. Operation O_{ij} has a process time p_{ijk} , as it may be different depending on the machine k where it is performed. In all the formulations that follow, the machine assignment is done using binary variables v_{ijk} , which equals 1 if operation O_{ij} is assigned on machine k and 0 otherwise.

3.2.1.2 Disjunctive or Precedence Based Formulation

In this formulation, binary variables x_{ijk} are used to denote the starting time of operation O_{ij} in machine k . Another set of binary variables $z_{iji'j'k}$, is equal to 1 if operation O_{ij} precedes operation $O_{i'j'}$ in machine k .

The complete formulation can be written as follows:

$$\text{Minimize } z = C_{max} \quad (3.1)$$

Subject to:

$$C_{max} \geq x_{ijk} + ps_{ijk} * v_{ijk} \quad \forall i, j, k \quad (3.2)$$

$$\sum_k (x_{ijk} + ps_{ijk} * v_{ijk}) \leq \sum_k x_{ij+1k} \quad \forall i, j \quad (3.3)$$

$$x_{ijk} \geq x_{i'j'k} + p_{ijk} - M * z_{iji'j'k} \quad \forall i' > i, j, j', k \in M_{ij} \cap M_{i'j'} \quad (3.4)$$

$$x_{i'j'k} \geq x_{ijk} + p_{i'j'k} - M * (1 - z_{iji'j'k}) \quad \forall i' > i, j, j', k \in M_{ij} \cap M_{i'j'} \quad (3.5)$$

$$v_{ijk} \leq a_{ijk} \quad \forall i, j \quad (3.6)$$

$$\sum_k v_{ijk} = 1 \quad \forall i, j \quad (3.7)$$

$$x_{ijk} \leq M * v_{ijk} \quad \forall i, j, k \in M_{ij} \quad (3.8)$$

Where equation (3.1) is the objective function and (3.2) ensures that the C_{max} is bigger or equal than the end of the last task. Constraints (3.3) ensure that all the operations within a job are executed in order. The non-overlap of tasks in a machine is guaranteed by constraints (3.4) and (3.5). Operations can only be assigned to their capable machines per (3.6). All operations must be assigned to a machine an sequence once per (3.7). Moreover, an operation can only have a starting time in machine k if it has been assigned to that machine by (3.8).

This model was first presented by Mane for the simple Job Shop Scheduling problem in 1960 [Manne, 1960]. Özgüven et al [Özgüven et al., 2010] extended this kind formulation for the Flexible Job Shop scheduling problem with process plan flexibility. In their experimentation, they demonstrate that their MILP model they present outperforms a heuristic proposed by Fattahi [Fattahi et al., 2007].

Gao et al [Gao et al., 2006] used a similar model with preventive maintenance tasks, adding variables c_{ij} for the completion time of operations. Moreover, Imanipour [Imanipour, 2006] used it for a problem with sequent dependant set-up time and Moradi et al for another bi-objective FJSP with maintenance [Moradi et al., 2011]. In addition, Kim and Egbel [Kim and Egbelu, 1999] used a precedence based model with starting times s_{ij} for each operation. They solved a set of instances with both the exact method and two heuristics, one of which is able to obtain optimal solutions in all the tested instances.

3.2.1.3 Time-Indexed Formulation

In this formulation, decision variables x_{ijk} are replaced by binary variables x_{ijkt} , which are equal to 1 if operation O_{ij} starts at time t at machine k .

The complete formulation can be written as follows:

$$\text{Minimize } z = C_{max} \quad (3.9)$$

Subject to:

$$C_{max} \geq \sum_{k \in M_{ij}} \sum_t (t + p_{ijk}) * x_{ijkt} \quad \forall j, i = \text{last } i \in J \quad (3.10)$$

$$\sum_t x_{ijkt} = 1 \quad \forall i, j, k \in M_{ij} \quad (3.11)$$

$$\sum_j \sum_i \sum_{t'=(t-p_{ijk}+1)}^t x_{ijkt} \leq 1 \quad \forall k, t \quad (3.12)$$

$$\sum_{k \in M_{ij}} \sum_{t=0}^{u-p_{ijk}} x_{ijkt} - \sum_{k' \in M_{i+1,j}} \sum_{t'=0}^{t'=u} x_{i+1,jk't'} \geq 0 \quad \forall t, i \neq \text{last}(i), j \quad (3.13)$$

$$v_{ijk} \leq a_{ijk} \quad \forall i, j \quad (3.14)$$

$$\sum_k v_{ijk} = 1 \quad \forall i, j \quad (3.15)$$

$$\sum_t x_{ijkt} \leq M * v_{ijk} \quad \forall i, j, k \in M_{ij} \quad (3.16)$$

Where (3.9) is the objective function and (3.10) the maximum makespan calculation. All operations are started exactly once per (3.11) are common to the previous model. The non-overlap of tasks in a machine is guaranteed by constraints (3.12). Precedence constraints in equations (3.13) ensure that operations from the same job are done in order. To end with, constraints (3.14) to (3.16) are the same as constraints (3.6) and (3.7) from the previous model. Operations can only be assigned to their capable machines per (3.14). All operations must be assigned to a machine an sequence once per (3.15). Moreover, an operation can only start any time in machine k if it has been assigned to that machine by (3.16).

This formulation was first presented by Kondili [Kondili et al., 1988] for the Job Shop Scheduling problem. Yong-Min investigated [Leffler, 2015] valid inequalities for its FSJP extension. In addition, Thomalla [Thomalla, 2001] and Gomes et al. [Gomes and Barbosa-Povoa, 2005] applied this model to a FJSP with parallel machines. Thomalla used a Lagrangian relaxation and reported an almost linear solution time. Gomes et al. applied it to a part manufacturing industry that operates on a make-to-order basis.

3.2.1.4 Rank-Based or Sequence Position Formulation

In this formulation, variables x_{ijkl} are equal to 1 if operation O_{ij} is scheduled at the l -th position on machine k and 0 otherwise. In addition, h_{kl} denotes the start time of the job at the l -th position

of machine k .

The complete formulation can be written as follows:

$$\text{Minimize } z = C_{max} \quad (3.17)$$

Subject to:

$$C_{max} \geq h_{kL} + \sum_i \sum_j p_{ijk} * x_{ijkL} \quad \forall k, L = last(l) \quad (3.18)$$

$$\sum_i \sum_j x_{ijkL} = 1 \quad \forall k, l \quad (3.19)$$

$$h_{kl} + \sum_i \sum_j p_{ijk} * x_{ijkL} \leq h_{kl+1} \quad \forall k, l \quad (3.20)$$

$$\sum_l x_{ijkL} \leq v_{ijk} \quad \forall i, j, k \in M_{ij} \quad (3.21)$$

$$h_{kl} + p_{ijk} \leq V * (1 - x_{ijkL}) + V * (1 - x_{ij+1k'l'}) + h_{k'l'} \quad \forall i, j, l, l', k \in M_{ij} \text{ and } k' \in M_{ij+1} \quad (3.22)$$

$$\sum_k v_{ijk} = 1 \quad \forall i, j \quad (3.23)$$

$$v_{ijk} \leq a_{ijk} \quad \forall i, j \quad (3.24)$$

Where (3.17) is the objective function. Per (3.18), the value of C_{max} must be bigger than the start time of the last operation of each machine plus the length of that operation. Non-overlap of operations in a machine is ensured per constraints (3.19) and (3.20). The first set ensures that only one operation is assigned for each position l and the second set ensures that the time assigned to each position is disjoint. Constraints (3.21) imply that each operation is assigned to a single slot and only if it is assigned to that machine. Precedence constraints between operations of the same job are guaranteed per (3.22). To end with, constraints (3.23) state that each operation can only be assigned to a single machine. The chosen machine must be within the allowed machines per operation as per (3.24).

Wagner [Wagner, 1959] was the first one to introduce this formulation for the Job Shop scheduling problem. Lee et al [Lee et al., 2002] were the first ones to use it for FJSP. Afterwards, Fattahi has made an extensive use of it, applying it to a set of FJSP: general FJSP [Fattahi et al., 2007], taking overlapping into consideration [Fattahi et al., 2009] and dynamic scheduling [Fattahi and Fallahi, 2010].

3.2.1.5 Comparison Between the Three Formulations

As for the comparison between these three formulations (disjunctive, time-indexed and rank-based), Ku and Beck [Ku and Beck, 2016] made a thorough comparison of their performance for the JSP. They concluded that Manne's disjunctive formulation was the most efficient. In addition, the time-indexed formulation outperformed the rank-based formulation in small instances. Demir's benchmark on FJSP, [Demir and İşleyen, 2013] provides similar results, as the

formulation based on Manne's performs best for the FJSP. He also provided a more in depth study of the performance of the time-indexed formulation and the high impact the chosen length of the time period has in the model performance and the solution quality.

3.2.2 Job Shop Scheduling Problems with Operators

The simultaneous use of machines and operators is another distinctive characteristic of the short term scheduling for the airframe assembly line. Operator scheduling has rarely been considered for machine scheduling. Recently, Agnetis [Agnetis et al., 2011] introduced a Job Shop problem with one type of operator and only one operator per task. They use $JSO(n, p)$ to refer to a Job Shop Scheduling problem with n machines and p operators. They dealt with the operator as an additional constraint: at most p operations can be done at the same time. Sierra [M.R. Sierra, 2015] proposed a new scheduling generation scheme for this problem and used it to solve scenarios that included a maximum of 120 operations, 3 machines and 2 available operators.

However, none of them use mathematical models to solve this problem. On the contrary, Guyon et al. [Guyon et al., 2014] used a time indexed formulation to deal with a job-shop problem with human resource constraints. To do so, they added to the time-indexed formulation of the FJSP presented in section 3.2.1.3 a new set $e \in E$: the set of available resources. Also, they added another set of binary variables, r_{ekt} equal to 1 if and only if operator e is assigned to machine k during time period t and 0 otherwise. Furthermore, new constraints must be added. Constraints (3.25) ensure each resource is only assigned to one machine per time period. Constraints (3.26) stand for the simultaneous assignment of machines and resources for an activity.

$$\sum_k r_{ekt} = 1 \quad \forall e, t \quad (3.25)$$

$$\sum_e r_{ekt} \geq \sum_i \sum_j x_{ijkt} \quad \forall k, t \quad (3.26)$$

Guyon et al solved the problem using two decomposition-based techniques. They compared them to another existing methods in the literature: the direct solution of the MIP model, a method presented by Artigues [Artigues et al., 2009] and a heuristic. Their second method is a hybrid cut generation and branch and bound approach that outperforms other methods.

Nevertheless, to the best of my knowledge, no study has been conducted that includes the possibility of multiple modes and considers the operators profiles, as is the case in our problem.

3.2.3 Literature Review Conclusions

Taking all the prior into account, I can state that the scheduling of an aeronautical airframe assembly has the structure of a Flexible Job Shop Scheduling Problem with operators. This problem, has not been analysed in prior studies. Although some of its characteristics have been analysed separately, no joint study has been identified. Furthermore, some options, such as

multiple modes for the resources per task have not been addressed. Therefore, this case study is of interest both from the industrial and academic perspective.

3.3 Model Formulation

An MILP formulation has been developed. As in Guyon's [Guyon et al., 2014] model with operators I have used a time indexed formulation. Demir [Demir and İşleyen, 2013], in his review for FJSP stated that the main drawbacks for this formulation are related with the poor quality of the solutions if big time slots are used and the low performance if time slots are shortened. However, in this case, decisions on the line are made on a discrete time basis. Due to the existing production ratio, activity changes are done only twice per shift. In consequence, this lead to a natural length of the time periods of four hours. Using that time discretization, the model lead to optimal solutions within limited time and therefore this type of formulation was selected.

Table 3.2 lists the ten sets that are used. The airframes to be produced are denoted as set E and P represents the set of processes into which the assembly of each airframe, named element in the model, is divided. The set O represents the types of operators, divided into production (O^P) and non-production categories (O^{NP}). The machines are defined as set K . The time horizon is divided into time slots T , which are classified as morning, afternoon or night shift time slots. The duration of a slot is one of the input parameters. The total scheduling time horizon is defined by the cycle time of the different elements that need to be produced and is calculated as the lowest common multiple (LCM) of all the cycle times. Therefore, an integer number for each element is produced within this time horizon. C refers to the set of cycles in which the time is divided, C_e refers to the subsets of cycles of each element and $T_{(e,c)}$ refers to the subset of slots that belong to each cycle c of element e .

Input parameters provide information regarding each element's cycle time, the processes per element (including their workload, precedence relationships and resource consumption and the use of operators' time), the machines' availability and the existing buffers in the plant. Parameters are listed in Table 3.3.

The primary decision variables are two. Variables o_{pet} are equal to 1 if operators are working on process $p \in P$ of the element $e \in E$ in time slot $t \in T$ and 0 otherwise. Also, variables no_{peot} that define the number of operators of type $o \in O$, working in process $p \in P$ of element $e \in E$ during time slot $t \in T$. Table 3.4 provides a listing of all the variables.

Two different models were used. The first model minimizes the total number of operators. The second model minimizes the average size of the buffer in the plant throughout the operation time.

Table 3.2: Short Term Airframe Manufacturing Scheduling (MSP): Sets

E	Set of elements e that are produced
P	Set of processes p that must be performed
K	Set of machines k
O	Set of types of operators O
O^P	Subset of operator types o that belong to a production category
O^{NP}	Subset of operator types o that belong to a non-production category
T	Set of time slots t
C	Set of cycles c in which the time is divided
C_e	Subset of cycles c of each element
T_{ec}	Subset of time slots t that belong to each cycle c of the element e

Table 3.3: Short Term Airframe Manufacturing Scheduling (MSP): Parameters

Cycle times per element and time horizon	C_e LCM QC_e IT_{ec}	Cycle duration of each element $e \in E$ Lowest common multiple (of all C_e) Number of cycles for each element $e \in E$ in the time frame considered: LCM/C_e Initial time slot of the cycle c of element $e \in E$
Element and processes characteristics	W_{pe} MAX_{peot} K_{pek} I_p	Workload (hours) to be performed to complete a process $p \in P$ of an element $e \in E$ Maximum number of operators of the type $o \in O$ for process $p \in P$ of element $e \in E$ 1 the process $p \in P$ of element $ee \in E$ uses machine $k \in K$ and 0 otherwise 1 if process $p \in P$ can be interrupted and 0 otherwise
Precedences between Processes	$PR_{pp'}$ $IP_{pp'}$ $PL_{pp'}$ $L_{pp'}$	1 if there is a precedence relationship between $p, p' \in P$ and 0 otherwise 1 if there is a precedence relationship with zero time lag between $p, p' \in P$ and 0 otherwise 1 if there is a precedence relationship with at least a $L_{pp'}$ time lag between $p, p' \in P$ and 0 otherwise Duration of the minimum time lag between processes $p, p' \in P$ (hours)
Slot Definition	T M_t A_t N_t NN AL_{tp} PA_t NA_t	Slot duration (hours) 1 if time slot $t \in T$ belongs to a morning shift and 0 otherwise 1 if time slot $t \in T$ belongs to an afternoon shift and 0 otherwise 1 if time slot $t \in T$ belongs to a night shift and 0 otherwise Quantity of non-night slots 1 if in the time slot $t \in T$ it is allowed to work on process $p \in P$ and 0 otherwise Previous active time slot of time slot $t \in T$ Next active slot of slot $t \in T$
Machine Availability	Q_k	Number of machines $k \in K$ that are available
Buffer Definition	$B_{pp'}$ $WB_{pp'}$	1 if there is a buffer between processes $p, p' \in P$ and 0 otherwise Weight value of each the buffer $B_{pp'}$

Table 3.4: Short Term Airframe Manufacturing Scheduling (MSP): Variables

Operators assignment per slot and element	o	Total number of operators
	om_o	Total number of operators of type o who work morning shifts
	oa_o	Total numbers of operators of type o who work afternoon shifts
	o_{pet}	1 if there are operators working on process p of element e in time slot t and 0 otherwise
	no_{peot}	Number of operators of type o , working during time slot t , in process $p \in P$ for each element $e \in E$
	ot_{ot}	Number of operators of type o in time slot t
Slot assignment	s_{pet}	1 if process p of element e starts in time slot t and 0 otherwise
	f_{pet}	1 if process pP of element e ends in time slot t and 0 otherwise
WIP measure	$b_{ep't}$	Quantity of elements $e \in E$ that are in the buffer between processes $p, p' \in P$ during time slot t
	$pb_{ep'p'}$	Quantity of elements $e \in E$ that are in the buffer between processes $p, p' \in P$ when production starts
	tb	Total quantity of elements in the buffers through the scheduling time horizon
Machine assignment	m_{pekt}	1 if machine k is assigned to the process p of the element e in the time slot t and 0 otherwise

3.3.1 Model A: Minimizing the Number of Operators

$$\text{Minimize } z = o \quad (3.27)$$

$$\text{Subject to: } \sum_o \sum_t no_{peot} \times T = W_{pe} \quad \forall p, e, c | c \in C_e; t \in T_{ec} \quad (3.28)$$

$$m_{pekt} \geq o_{pet} \quad \forall p, e, k, t | K_{pek} = 1 \quad (3.29)$$

$$no_{peot} \leq o_{pet} MAX_{peot} \quad \forall p, e, o, t \quad (3.30)$$

$$\sum_t no_{peot} \geq o_{pet} \quad \forall p, e, t \quad (3.31)$$

$$o_{pet} \leq M_t + A_t \quad \forall p, e, t \quad (3.32)$$

$$\sum_{ep} m_{pekt} \leq Q_k \quad \forall k, t \quad (3.33)$$

$$ot_{ot} = \sum_p \sum_e no_{peot} \quad \forall t, o | o \in O^p \quad (3.34)$$

$$om_o \geq no_{peot} \quad \forall o | o \in O^p, t | M_o = 1 \quad (3.35)$$

$$oa_o \geq no_{peot} \quad \forall o | o \in O^p, t | A_t = 1 \quad (3.36)$$

$$o = \sum_o (om_o + oa_o) \quad (3.37)$$

$$no_{peot} = 0 \quad \forall e, p, e, o, t | N_t = 1 \quad (3.38)$$

$$no_{peot} \geq o_{pet} \quad \text{if } t = IT_{ec} \quad \forall p, e, o, t | t \in T_{ec} \quad (3.39)$$

$$s_{pet} \geq o_{pet} - o_{pePA_t} \quad \text{if } t \neq T_{ec} \quad \forall p, e, c | t \in T_{ec} \quad (3.40)$$

$$\sum_t s_{pet} = QC_e \quad \forall e, p \quad (3.41)$$

$$\sum_t f_{pet} = QC_e \quad \forall e, p \quad (3.42)$$

$$o_{pet} \leq s_{pet} + o_{pePA_t} \quad \forall p, e, t, c | I_p = 1; c \in C_e; t \neq IT_{ec}; t \in T_{ec} \quad (3.43)$$

$$f_{pet} \geq o_{pePA(t)} - o_{pet} \quad \forall p, e, c | t \in T_{ec} \quad (3.44)$$

$$f_{pet} \times W_{pe} \leq \sum_{t' < t} no_{peot} \times T \quad \forall p, e, t \quad (3.45)$$

$$o_{p'eIT(ec)} = 0 \quad \forall e, c, p', t | \sum_p P_{p,p'} = 1 \quad (3.46)$$

$$\sum_{t'} no_{peot'} \times T \geq s_{p'et} W_{ep} \quad | IT(ec) \leq s' \leq s \quad \forall e, p, p', t, cy | t \in T_{ec}; PR_{p,p'} = 1 \quad (3.47)$$

$$o_{pet} + o_{p'et+n} \leq 1 \quad \forall e, p, p', t, n | PL_{pp'} = 1; n = 0, 1, \dots, \frac{L_{pp'}}{T} \quad (3.48)$$

$$o_{peIT_{ec}} = 0 \quad \forall e, p, p', t, c | PL_{pp'} = 1 \quad (3.49)$$

$$f_{pet} = s_{p'et + \frac{L_{pp'}}{T} + 1} \quad \forall e, p, p', t | L_{pp'} = 1 \quad (3.50)$$

$$f_{pet} \leq m_{ep'kt+n} \quad \forall e, p, p', k, t | PL_{p,p'} = 1; K_{pek} = 1; n = 0, 1, \dots, \frac{TSFT_{p,p'}}{SD} \quad (3.51)$$

$$f_{pet} = s_{peNA_t} \quad \forall e, t, p, p' | IP_{pp'} = 1 \quad (3.52)$$

$$o_{pet}, s_{pet}, f_{pet}, m_{pekt} \in \{0, 1\} \forall p \in P, e \in E, t \in T, k \in K \quad (3.53)$$

3.3.2 Model B: Minimizing the Average Size of the Buffer in the Plant

All the constraints used in the first model in addition to the following:

$$\text{Minimize } z' = M \times tb + o \quad (3.54)$$

Subject to:

$$b_{epp't} = pb_{epp'} \quad \text{if } t = IT_{ec} \quad (3.55)$$

$$b_{epp't} = b_{epp't-1} + f_{ept-1} - s_{ep't} \quad \text{if } t = IT_{ec} \quad \forall e, p, p', t, c | t \in T_{ec}; BP_{pp'} = 1 \quad (3.56)$$

$$pb_{epp'} \geq 0 \quad \forall e, p, p' | BP_{pp'} = 1 \quad (3.57)$$

$$pb_{epp'} \leq QC_e \quad \forall e, p, p' | BP_{pp'} = 1 \quad (3.58)$$

$$tb = \sum_e \sum_p \sum_{p'} \sum_t b_{epp't} \times WB_{pp'} \quad \forall e, p, p' | BP_{pp'} = 1 \quad (3.59)$$

Objective Function Where the objective function (3.27) is the minimization of the number of operators and (3.54) the minimization of the average size of the buffer in the plant.

Workload and Machine Allocation per Process Constraint (3.28) ensures that the workload scheduled for process p of element e in all time slots t of a cycle multiplied by the duration of the slots is at least the total process workload for that element W_{ep} . The simultaneous assignment of the machines and operators to the process of an element is guaranteed by constraints (3.29). Constraints (3.30) and (3.31) refer to the operators that are assigned to a process. The number of operators of type o working on process p for element e in time slot t (no_{peot}) must be less than its maximum (MAX_{peot}) (3.30) and if operators are working on a process for a slot then an operator type must be assigned ($\sum_o no_{peot} \geq o_{pet}$) (3.31). Furthermore, per (3.32) operators only work on a process during a slot if this slot belongs a morning or afternoon shift.

Machine Constraints The number of machines k that are assigned during a slot cannot be more than the machine availability Q_k per constraint (3.33).

Total Number of Operators The total number of operators that are needed per type and shift is calculated by (3.34). Constraints (3.35) through (3.37) limit the total number of operators, which is the sum of the morning operators (3.35) and afternoon operators (3.36). Operators are not permitted to work during the night shift per constraint (3.38).

Process Start and End When evaluating the first slot, a process begins (s_{pet}) when an operator (o_{pet}) begins working in this process (3.39). For the remaining slots, a process begins (s_{pet}) when an operator (o_{pet}) begins working and no operators were working in the previous active slot (o_{pePA_t})(3.40). The number of times that a process begins/ends (s_{pet}) must equal the number of elements to be manufactured (QCe) (3.41 - 3.42).

A process cannot be interrupted once it has started if non pre-emption applies to it per (3.43). To determine the end of a process, the value of ($o_{pePA_t} - o_{pet}$) is taken into account in constraint (3.44):

- $o_{pePA_t} - o_{pet} = 0$ if process p is active after both time slot t and its previous active slot or inactive after both.
- $o_{pePA_t} - o_{pet} = -1$ if process p starts in t .
- $o_{pePA_t} - o_{pet} = 1$ if process p is inactive after time slot t and active in the previous active slot PA_t .

Moreover, constraint (3.45) ensures that the end of a process can only occur if the addition of the prior workload is equal to the total amount that is required.

Precedence Relationships Precedence relationships are managed with constraints (3.46 - 3.52). Constraints (3.46-3.47) address general precedence constraints and (3.48-3.51) address time lag constraints (processes that must begin exactly $L_{pp'}$ time after their predecessor). Constraint (3.51) addresses the machine occupation during the time lag. Constraint (3.52) refers to a zero time lag precedence.

Domain Constraints are (3.53).

The following constraints in addition to the prior constraints form the second model:

Buffer Objective Function The objective function (3.54) is a weighted sum of the number of elements in buffers (tb) and the total number of operators (o). In that equation, M is a big enough number to ensure the buffer size minimization is prioritized. If I had not used the total number of operators in the objective function, that would have resulted on unbounded results for the number of operators.

Buffer Allocation Constraints (3.55) through (3.59) refer to the buffer occupation during the time horizon. The buffer that corresponds to the first slot is equal to the quantity that the system uses to begin the production. The buffer of the subsequent slots (b_{eppt}) is equal to the number of the previous slot (b_{eppt-1} , b_{eppt}) and a balance of the income and output of this buffer in that slot change ($f_{pet-1} - s_{p'et}$) (3.55 and 3.56). The initial value of the buffers of elements (pb_{eppt})

Table 3.5: Working Hours Per Process and Airframe Model

Airframe	Process Number								
	1	2	3	4	5	6	7	8	9
Model-A LH	4	8	16	8	60	48	12	8	12
Model-A RH	4	8	20	8	52	32	8	8	12
Model-B LH	8	12	16	8	56	40	12	8	12
Model-B RH	8	12	20	8	48	48	8	8	12

must be greater than or equal to 0 (3.57) and less than or equal to the number of elements that must be produced (QC_e) (3.58). Finally, the total number of elements through all the slots (tb) is equal to the weight sum of each buffer ($\sum_e \sum_p \sum_{p'} \sum_t b_{ep p' t} * WB_{pp'}$) (3.59).

3.4 Experimentation

For the experimentation, the models were implemented in AIMMS [Roelofs and Bisschop, 2011] and solved using an Intel Core i7 pro with 8 GbB of RAM running AIMMS with CPLEX under Windows 10. Solutions were provided within an adequate computational time. In the worst case scenario, a solution was provided in less than 4 hours, whereas a planner spends approximately 40 hours to manually calculate a solution without using any computational methods.

Tests were performed using real-life data and considered real-life production times and the product mix from prior years. Because of confidentiality constraints, process workloads have been modified for the experimentation I will present.

The workload per process and airframe are common in all the instances and is provided in Table 3.5. They vary from 4 to 60 man-hours per process. On the assembly line, work is assigned each 4 hours and therefore, the slot duration has been set to this length. In consequence, production times are also rounded to multiples of 4. For example, the average time for process 2 of Model-A-LH is 6.7 hours and it will be rounded to 8 hours. I rounded up instead of round down because processing time is more frequently exceeded than reduced in real operation.

The nine processes that were explained in Chapter 3.1 must be performed in order for each airframe. (Process 1, Process 2, ... Process 9). Furthermore, there is an immediate precedence between Processes 8 and 9. Processes 1, 2, 4 and 8 cannot have pre-emption. The time lag ($L_{pp'}$) between processes 3 and 4 should be at least 8 hours. All machines are available during morning and afternoon shifts, with the exception of Cell F (process 8), which is only available in the afternoon.

The experimentation is divided into three steps. In a first step, an instance with the production times on Table 3.5 and all possible combinations of cycle times for a time horizon that lasted a maximum of 12 days, was solved minimizing the total number of operators. In the second step the experimentation was repeated minimizing the buffer. Finally, in the third step, for the first three instances (time horizon of 4, 5 and 6 days), I experimented with several numbers of operators to

Table 3.6: Results for the Minimization of the Number of Operators

Instance	Time H. (days)	Var(Int)	Constr.	Sol. Time (sec)	Num Op*	Average Buffer
Op/4/4	4	4622(4583)	11252	15	21	32.75
Op/5/5	5	5774 (5727)	15716	36	16	28.65
Op/6/6	6	6926 (6871)	20852	33	14	18.13
Op/4/6	12	13838 (13735)	37610	2,783	18	49.29
Op/6/4	12	13838 (13735)	29617	1,300	17	48.81

obtain the optimal solution in terms of buffer. That is, I obtained the Pareto Front for the two objective functions. From the used instances, the most common on the workshop are those of 4, 5 and 6 working days. The maximum time horizon is 12 days because a production pattern of more than 15 calendar days is rarely used in practice. Conversely, a time horizon of less than 4 days is not possible because of Model-A's total workload.

The scheduling output includes a bar chart where each process has an allocated time slot and an assigned number of operators per time slot. Figure 3.3 provides the results for the first two days for the example Op/4/4. The different processes are listed on rows. There is one column per time period (half a shift = 4 hours). The colored cells are the ones when a process is being done and the number inside the cell is the number of operators assigned to that execution of the process. For example, on the first half shift there are two Model-A-LH being processed: one is going through Process 1 and another one through Process 3. They are using one operator each. In all, 10 operators are needed during that half shift.

Table 3.6 provides the results of the first step of the experimentation when I solved the first model for solely minimizing the number of workers. After that, I calculated the average buffer in the plant for those solutions. In Table 3.7 I provide the results for the average size of the buffer minimization and the corresponding number of workers.

Both tables have the same structure. The first column provides the name of the instance. Instances are named with a two letter code that depends on the objective function that used to solve it ("Op" refers to the number of operators objective function and "Bf" refers to the average number of elements in the buffer objective function) followed by Model-A's cycle time and Model-B's cycle time. The second column (**Time H.**) shows the scheduling time horizon. Columns three and four (**Var (Int)** and **Constr.**) refer to the number of variables and constraints in the model, respectively. **Solving times** are measured in seconds and listed in column five. All instances have been solved to obtain the optimal outcome. Finally, column six (**Num Op**) refers to the total number of operators in the solution and column seven (**Average buffer**) refers to the average number of elements in the buffers during the scheduling horizon.

As expected, minimizing one criterion has a negative impact on the other criterion. For example, for instance Op/4/4, we obtain 21 workers and 34.75 elements. The solution minimizing the buffer of the same instance (Bf/4/4) uses 6 more workers (27) but less than half the average

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Figure 3.3: First Two days of the Solution Bar Chart for instance Op/4/4

Table 3.7: Results for the Minimization of the Average Buffer

Instance	Time H. (days)	Var(Int)	Constr.	Sol. Time (sec)	Num Op	Average Buffer*
Bf/4/4	4	5122(5084)	11773	16	27	14.94
Bf/5/5	5	6394 (6348)	16357	39	20	9.85
Bf/6/6	6	7666 (7612)	21613	400	16	4.71
Bf/4/6	12	15298 (15196)	39091	7,537	21	6.73
Bf/6/4	12	15298 (15196)	39091	9,178	21	7.60

buffer size (14.95). A typical solution for combining two objectives would have been to transform everything to cost, and then minimize the cost. However, this traditional approach limits the decision maker to only one option. Based on the specific situation of the week, the decision maker could make a decision that prioritizes the number of workers or the size of the buffer, or something else in the middle. Therefore, in our third experimentation step we studied the entire range of possible solutions for instances 4-4, 5-5 and 6-6.

Results from the third step are plotted on Figure 3.4. A curve for the different solutions of each of the instances is provided. The first point is the minimum number of operators as calculated on step 1 (see Table 3.6). Then, I fixed the number of operators, adding an operator at a time and solving the resulting problem minimizing the average buffer. I stopped the experimentation for each instance when adding an extra worker did not provide a further improvement in the solution. The red squares highlight the dominated solutions. The circles point out the better solutions. Each point in the graph has a bar chart associated as the one that we can see in Figure 3.3.

Another relevant study to be made is the impact of the change of takt in the labor cost. Figure 3.5 shows the evolution of the labor cost (measured in total operator working days to be paid) for two cases. The red line compares the labor cost for the minimum operator solutions for each of the takts. The blue line compares the labor cost for the circled solutions from figure 3.3: the solutions with a better buffer - operator rate from my point of view. In both cases, it can be seen that the 5 days takt enables a more efficient use of the operators.

The comparison of the performance of the different takt times in terms of buffer is shown on figure 3.6. As in the previous figure, two solutions per takt are plotted: the one with the minimum buffer and the best buffer-operator trade off. In this case, the higher the takt, the lower the overall cost.

Although researchers generally use a common approach that translates everything to cost, that translation is not straight forward. In real life problems, production managers agreed that a translation is complicated and depending on each manager's perspective and external factors, different costs could be applied to the same item. That is the case here, when comparing the inventory (buffer) cost with the operator cost. Therefore, the use of a Pareto front instead was agreed as more suitable between the industry experts that were interviewed.

Figure 3.4: Number of Operators - Buffer Size Pareto Front

3.5 Conclusions & Further Research

Case Study Conclusions This chapter describes a case study for airframe assembly short term scheduling. This problem can be dealt with as a Flexible Job Shop Scheduling Problem with operators. The problem was solved for instances of up to 16 machines, 45 different processes and 30 operators. The model was used with real-life examples and tests were performed with scheduling horizons from 4 to 12 working days.

Furthermore, the conclusions of this case study are of direct application in the aeronautic industry, where reducing the costs that are incurred for human resources or work in progress is an important source of competitiveness. A reduction in the number of workers on an assembly line directly decreases the costs related to human resources. Additionally, a decrease in the intermediate stock is greatly appreciated by managers because this not only results in financial savings but also reduces the possibility of damaging the products and incurring reparation costs.

When it comes to the comparison between the two objective functions (minimizing the number

Figure 3.5: Labor Cost Comparison For Different Cycle Times

of operators or minimizing the buffer size), the use of a Pareto front provides more flexibility than a fixed weighed sum between the two objectives. Factories are more and more exposed to a changing environment and this approach enables the user to adapt the final decision to the current state of the factory, such as capacity to allocate spare workers, the amount of inventory or the price of the inventory.

This approach is only possible because the time needed to solve the problem has been greatly reduced. Manual scheduling process took more than 40 hours whereas the model solution time was 2.6 hours for the harder instance. The time needed to solve the problem is in fact, one of the primary advantages of the model that is presented in this study. The problem I have addressed is a non-typical linear process with resources that could be configured, elements that visit a workstation more than once, compulsory waiting times, and workers that only work certain shifts. Commercial ERP software, such as SAP, is unable to solve and optimize this type of production process.

Future Research

Figure 3.6: Buffer Cost Comparison for Different Cycle Times

Future studies could improve the model's performance. Although all the instances in this problem have been solved to optimality, future studies could solve larger problems such as including operators who are shared by different mixed model assembly lines. To solve these larger problems, parallel computing could be tested. Future studies could also use decomposition approaches, constraint programming or other hybrid and meta-heuristic techniques. Finally, another interesting topic for future research is managing stochastic process times and machine failures.

Moreover, at the beginning of the problem definition, I have decided to fix the time horizon to the LCM of all the airframes' cycle time. This may lead to long time horizons and therefore, too long solving times. As an alternative, the cyclic characteristics of the problem could be scheduled, in order to identify a shorter feasible scheduling time horizon.

Use of the model for Part Manufacturing Scheduling

As it was stated in the beginning of this section, part manufacturing scheduling can also be classified within Machine Scheduling Problems. Therefore, it seems reasonable to check the

applicability of this model to a part manufacturing use case.

In the newest aircrafts, most of the parts are composite parts. In consequence, I have made a preliminary analysis on the scheduling problem for a composite manufacturing plant. As a result I have identify some features that would require a specific approach in order to extend the model. Those features are:

- Autoclave. Most composite parts need to be cured in an autoclave, which are expensive machines. In the autoclave, several parts can be cured at the same time, as long as they share a curing cycle and there is enough space for all of them. Therefore, the optimization of the use of the autoclave becomes an optimization problem itself very different to other jigs which are just allocated to one part at a time.
- Number of parts to be scheduled at a time. Together with the autoclave, this is the main issue to be addressed. The number of parts to be scheduled is much higher in a part manufacturing site than in an airframe assembly line. Also, cycle times are shorter and therefore, the time discretization of four hours may be too long. Using shorter time slots and scheduling more parts could result on poor processing times and require a different solution method.
- Raw Material's limited life-time. That constraint was not taken into account in the current model but could be easily added using maximal time lags between processes.

In conclusion, although part manufacturing scheduling belongs also to Machine Scheduling Problems, they would need a new in detail separate study and modelling approach.

Part III

Mid Term Scheduling for Airframe Manufacturing: Aggregate Production Planning Problems

In this part I will focus on the medium term planning of the airframe assembly lines. That is, the area that is highlighted from the *Aeronautical Supply Chain Planning Matrix* in Figure III.1. As it was seen in the literature review on chapter 2.4, to the best of my knowledge, there were no references regarding the scheduling within this time horizon for airframe manufacturing.

Figure III.1: Aeronautical Planning and Scheduling Matrix - APP

The strategy to deal with this problem has been similar to the one used in the previous part. To begin with, I selected a use case from the real industry: the medium term planning of the same airframe manufacturing assembly line I presented in the previous section. Section 4.1 is dedicated to the description of the existing problem. The literature review on aggregate production planning problems is explained in Section 4.2. In that section, I explain how the particular use case is related to the more general aggregate production planning problem and the existing models from the literature. A model for the use case problem is presented afterwards, in Section 4.3. This first model has inherited the current planning hypothesis used in the plant. It has turned out to be an easy to solve model because of its reduced size. In consequence, it was a great opportunity for a quick win in the plant. Implementation results are explained in Section 4.4.

Although that first model was of huge relevance for the airframe assembly line, its solution

was not challenging in terms of research. Therefore, I have chosen to provide an alternative view of the problem. In this additional view I added a more realistic modelling of the human resource cost. Also, I took into account sustainability parameters, related to energy consumption and CO_2 emissions. I believe this is a major contribution, as energy related factors will be more and more relevant for all industries in the coming years. Chapter 5 is dedicated to this second approach. The relevance of the added elements is discussed in Section 5.1. Afterwards, Section (5.2) explains more in detail how energy cost and consumption and human resource cost will be modelled. The complete formulation is explained in Section 5.3. As part of the experimentation, I have studied what impact has the use of different objective functions in the production plan footprint (energy used and CO_2 produced through the year). That is presented in Section 5.4. To end with, final conclusions are explained in Section 5.5.

ACTUAL AGGREGATE PRODUCTION PLANNING MODEL

4.1 Problem Description

At the beginning of a production year in an airframe assembly line, a first rough capacity vs workload analysis is performed in order to ensure there is enough capacity to deliver all the products. Afterwards, a more detailed production plan is generated. At that step, the production modes for each time period are set. For example, if during a year (with an estimated length of 202 working days) 42 units of each product must be delivered, that can be split into 100 days delivering 1 product each 4 days and 102 days delivering 1 product each 6 days. Each of this production modes establishes a production rate and also a jig configuration.

In this part I will focus on the choice of the production modes per period in order to comply with the overall yearly demand. The main decision, therefore, is to adjust the production mode and therefore the workforce per period. I will use as a case study the same plant that in the previous part.

In that assembly line, there is a finite number of production rates. Cycle times of less than 4 days are not possible because of the lead time of the longer processes. On the other side, production managers stated that longer cycle times reduce the learning factor caused by the repetition of works and thus are undesirable. In practice, cycle times of more than 10 days are barely used. Hence, there are 7 possible cycle times for our case study: from 4 to 10 days cycle time.

On top of this, there are 8 possible delivery rates: 0, 2 or 4 units per product variant. For example, with 4 days of cycle time the plant can produce at a rate that 0/0, 0/2, 0/4, 2/0, 2/2, 2/4, 4/0, 4/2 or 4/4 elements are produced at the end of the cycle. (Where 2/4 means 2 units of variant A and 4 units of variant B).

Taking into account the 7 cycle times and the 8 delivery rates, there are 56 different production

Month	January					February				Mars				April				May				June			
Calendar Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Detailed Schedule	4					12				50															

Figure 4.1: Six Months' Schedule Planning

rates. Before this work, production rates were decided and then a detailed schedule for the selected production rates was generated. The detailed scheduling generation was very time consuming and it could even lead to unfeasible solutions. As a result, decision makers usually chose previously used production rates even if they led to less efficient solutions. With the implementation of the model from Part II this has changed. Now, a detailed scheduling for a production rate can be calculated within minutes. Therefore, a production rate is easily translated into a fixed number of operators per shift (morning / late) and thus a labor cost per cycle.

Changeovers are also taken into account. Different production rates mean different machine configurations. This changes take time. More than that, a changeover can be a source of machine failures and other non-conformities. For this reason, there is a limited amount of changeovers allowed for the year.

In summary, the problem I will address can be stated as follows: given a yearly demand of product models (A and B in this use case), a production schedule must be chosen for each time period taking into account that:

- There is also a maximum and minimum number of days to be scheduled per year. That flexibility comes from the fact that work can be scheduled in some Saturdays and free days if needed.
- The total number of units per product produced must be equal to its demand, with a small tolerance. Some extra / less elements are accepted at this scheduling step.
- The number of different production modes to be used is limited. There is a changeover cost associated to each change between production modes. This cost is the jig re-configuration cost and also other cost associated to a higher risk of non-conformities at the beginning of the new production mode.
- The planning objective is to minimize the labor cost, calculated as the sum of the number of operators used in all the scheduled shifts.

The resulting solution is a yearly calendar where a detailed schedule is assigned for each week. An example can be seen in Figure 4.1, where three different production schedules are planned for the first half of the year.

4.2 Literature Review

The problem in this part can be considered within Aggregate Production Planning (APP) Problems. Baykasoglu defined these problems as those dealing with medium-term capacity planning over a 2 to 18 month planning horizon [Baykasoglu, 2001]. In accordance with Cheraghalikhani [Cheraghalikhani et al., 2019], APP models aim to *"find a production rate and some level of work force that will minimize the costs associated with meeting a known demand"*. In fact, the planner must optimize the production plan making decisions regarding the adjustment of production rates, employment levels, inventory levels and back-ordering rates as well as subcontracting [Chakraborty et al., 2015], [Buffa and Miller, 1979]. As an aggregate level of planning, there is no need for APP to provide neither detailed material and capacity resource requirements for individual products nor detailed schedules for facilities and personnel [Baykasoglu, 2001].

Nam and Logendran [Nam and Logendran, 1992] provided in 1992 an extensive state of the art review for Aggregate Production Planning Problems, in which 140 journal articles and 14 books were categorized into optimal and near-optimal classifications with respect to models and methodologies. Since then, no other review had been presented until 2018, when Cheraghalikhani et al [Cheraghalikhani et al., 2019] updated the review from Nam and Logendran with the articles published in the last decade. They used three aspects to classify them: number of objective functions (single or multiple), type of data (deterministic, fuzzy or stochastic) and issues under study. Those issues were divided into primary issues and additional or important issues. The primary issues have been present in most APP models and were already listed by Silver in 1976 [Silver, 1976]. They are the following:

- Market demand.
- Inventory.
- Backorder: whether backordering is allowed and to what extent.
- Production capacity: including machine and manpower capacity.
- Warehouse space.
- Costs of production: including production costs, inventory holding costs and backordering costs.
- Subcontracting.
- Labor level: number of workers per period, including regular and extra time.
- Hiring and layoff cost.
- Product prices.

Together with that primary issues, Cheraghalikhani et al selected some additional issues that had also been addressed in the most recent papers [Cheraghalikhani et al., 2019]. These include aspects related to the growing flexibility and complexity in manufacturing environments, such as multiple products, multiple markets, multiple manufacturing plants or overall supply chain optimization. Also, they drew the attention to some specific labor characteristics with direct impact on aggregate production planning: learning curve effect, labor skill, legal restrictions, labor training, labor productivity and utilization, constant level for labors, worker productivity and productivity losses. Moreover, other issues were related to product characteristics, such as the moment of the product life cycle, its perishability or the management of defective products, and customer satisfaction level. In addition, they drew the attention to the existence of set up time and costs and machine utilization constraints, which are usually neglected in aggregate production planning. To end with, they included other aspects such as the degree of decision-maker's satisfaction with the solution, the time value of money and other financial concepts.

The problem I will be addressing has a single objective (minimize production cost) and uses deterministic data. Not all the primary APP issues are relevant for our problem. As a result some of them, such as product price or subcontracting have not been taken into consideration. Moreover, some of the referred to as "Additional Issues" by [Cheraghalikhani et al., 2019] have been included. In all, the hypothesis have been:

For **primary issues**:

- **Market demand.** There is a fixed annual demand per product model.
- **Inventory and back-ordering.** They are not explicitly considered. As far as the total produced units are enough for the market, it is assumed that the solution will be feasible in terms of inventory and back-ordering
- **Production capacity.** I will consider the aggregate planning as a sequence of pre-calculated feasible production schedules. Therefore, production capacity is taken into account with both machine and labor constraints.
- **Labor level.** Minimizing the labor level is the major driver of our problem. Labor productivity is included as I will use real production schedules as a basis.
- **Costs of production.** In this first approach, only labor costs are taken into account. Inventory or backordering costs are neglected. However, inventory costs will be discussed in the next chapter.
- **Subcontracting.** Subcontracting the whole assembly is not an option in this case. Nevertheless, some of the assembly processes can be subcontracted. However, that has already been taken into account in the detailed schedule calculation and different subcontracting

scenarios would lead to different detailed schedules, and therefore different inputs for this planning step.

- **Product Price.** This is not relevant for our use case.

For **additional issues**:

- **Labor characteristics.** Labor utilization and skills are included as they have considered in the calculation of the baseline schedules I will use as an input.
- **Set Up decision.** The impact of Set Ups is taken into account. In fact, the number of change overs will be limited by the model.
- **Machines' utilization.** This is included as it is considered in the calculation of the baseline schedules I will use as an input.

Among the articles reviewed by Cheraghalikhani [Cheraghalikhani et al., 2019], 16 are deterministic single-objective models. Half of them deal with important issues on labor constraints and three include set up decisions. Machine utilization is not considered by any of them. Withal, those three issues I will deal with have not been previously addressed jointly in any of the references. As for the solution method, I will use a MILP model solved using MS Excel and Open Solver [Mason, 2012]. The use of these kind of solvers is also a frequent approach within the reviewed papers.

In summary, I will be dealing with an aggregate production planning problem that includes some of the important aspects identified in recent research papers, and therefore of common interest in other industries. Nevertheless, the issues I will take into account have not been jointly addressed yet.

4.3 Model Formulation

With the problem requirements explained in the previous section, a MILP model has been formulated. In fact, the aggregate production planning problem for our airframe assembly line can be formulated as a multi-dimensional knapsack problem [Martello, 1990].

The model has four sets. They are listed on Table 4.1. The set "Product Variant (**V**)" refers to the different product models (A, B in this case study). At this step, I will use as an input the total number of airframes that needs to be delivered. Then, the detailed production schedule splits that overall demand into left hand side and right hand side airframes for this case. Therefore, if for a schedule 2 units of model (variant) A are delivered, the detailed schedule corresponds to a LH and a RH delivery.

Table 4.2 contains the model parameters and Table 4.3 the list of variables that have been defined.

Table 4.1: Medium Term Scheduling Sets

O	Set of schedule options to produce
M	Set of months of the year
S	Set of shifts
V	Set of product variants

Table 4.2: Medium Term Scheduling Parameters

Operators	OP_{so}	No. of operators used during shifts $s \in S$ in Option $o \in O$
	OC_o	Operator cost per cycle in Option $o \in O$
Production	P_{vo}	No. of pieces of Variant $v \in V$ produced per cycle in Option $o \in O$
	UP_v	Max. no of units of Variant $v \in V$ to be produced in the year
	LP_v	Min. no of units of Variant $v \in V$ to be produced in the year
	MO	Maximum number of changes allowed per year
Time	CT_o	Cycle time (in days) required for schedule Option $o \in O$
	UD	Maximum working days of the planning period
	LD	Minimum working days of the planning period

Table 4.3: Medium Term Scheduling Variables

u_o	Number of times Option o is used
α_o	1 if Option o is used, 0 otherwise
no	Total operator working days used during the year

The complete formulation is as follows:

$$\text{Minimize } z = no \quad (4.1)$$

Subject to:

$$\sum_s \sum_o OP_{so} \times CT_o \times u_o = no \quad (4.2)$$

$$\sum_o P_{vo} \times u_o \leq UP_v \quad \forall o \in O \quad (4.3)$$

$$\sum_o P_{vo} \times u_o \geq LP_v \quad \forall o \in O \quad (4.4)$$

$$\sum_o CT_o \times u_o \leq UD \quad \forall o \in O \quad (4.5)$$

$$\sum_o CT_o \times u_o \geq LD \quad \forall o \in O \quad (4.6)$$

$$u_o \leq M \times \alpha_o \quad \forall o \in O \quad (4.7)$$

$$\sum_o \alpha_o \leq MO \quad \forall o \in O \quad (4.8)$$

$$\alpha_o \in \{0, 1\}; u_o \in \mathbb{Z} \quad \forall o \in O \quad (4.9)$$

Where (4.1) is the objective function. The value of the total number of operators is calculated by (4.2). The number of units per variant must be between the maximum and minimum number of allowed production. That is ensured by constraints (4.3) and (4.4). In addition, the number of days used is controlled by constraints (4.5) and (4.6). Finally, the number of used options are dealt with in constraints (4.7) and (4.8). Constraints (4.9) are the domain constraints.

4.4 Implementation

Due to the small dimension of this problem for the use case, it was solved using Excel and Open Solver [Mason, 2012]. This decision enabled a better exchange with the users and ensured the usability of the model in the future.

The MS Excel file that was created can be seen in Figure 4.2. The blue lines have the information on the different manufacturing options. In the left hand side is the Input Data that characterizes the option for the annual planning: cycle time, number of operators per shift and number of airframes produced per variant. Output data per option is in the right hand side. The most important is the first column, which informs about the number of times that option is selected. The other columns show calculated data: the total airframes per variant produced with that option and the number of operators used per shift. The number of days available and the expected production per airframe must be included in the red-framed cells. In there, blue shadowed cells are the inputs and yellow cells the output. As an example, between 200 and 300 production days are allowed to produce 10 units of product variant A and 54 to 56 units of product variant B with at most 4 options. The solution is to use 19 times option 21, 5 times option 49 and 3 times option 53.

Different Input Data sets were tested. For all of them, solutions were provided in less than fifteen minutes, running in an Intel core i5, 2.4 GHz and 8GB RAM. This solution times totally outperformed the existing manual methods, with whom several dates were needed for having a feasible, often sub-optimal, solution.

Input Data								Output Data							
Option	Jig Config.	Cycle (days)	A Prod Rate	B Prod Rate	Morning Oper.	Late Shift Oper.	Daily Oper.	Number of times	Used Days	Variant A Produced	Variant B Produced	Used?	Morning Oper.	Late Shift Oper.	Total Oper.
1	2xA, 2xB	4	2	2	10	9	19	0	0	0	0	0	0	0	0
20	2xA	6	2	0	4	3	7	0	0	0	0	0	0	0	0
21	2xB	6	0	2	4	3	7	0	0	0	0	0	0	0	0
22	2xA	6	2	0	7	0	7	0	0	0	0	0	0	0	0
23	2xB	6	0	2	6	0	6	0	0	0	0	0	0	0	0
24	-	6	0	0	0	0	0	0	0	0	0	0	0	0	0
25	2xA, 2xB	7	2	2	6	5	11	0	0	0	0	0	0	0	0
26	4xA	7	4	0	6	5	11	0	0	0	0	0	0	0	0
46	2xA	9	2	0	5	0	5	0	0	0	0	0	0	0	0
47	2xB	9	0	2	4	0	4	0	0	0	0	0	0	0	0
48	-	9	0	0	0	0	0	0	0	0	0	0	0	0	0
49	2xA, 2xB	10	2	2	4	4	8	5	50	10	10	0	200	200	400
50	4xA	10	4	0	4	4	8	0	0	0	0	0	0	0	0
51	4xB	10	0	4	4	4	8	0	0	0	0	0	0	0	0
52	2xA	10	2	0	2	2	4	0	0	0	0	0	0	0	0
53	2xB	10	0	2	2	2	4	3	30	0	6	0	60	60	120
54	2xA	10	2	0	4	0	4	0	0	0	0	0	0	0	0
55	2xB	10	0	2	4	0	4	0	0	0	0	0	0	0	0
56	-	10	0	0	0	0	0	0	0	0	0	0	0	0	0

Maximum	Used Days	Variant A Prod.	Variant B Prod.	Options Used	Morning Op.	Late Shift Op.	Total Op.	Mean Morning Shift Op.	Mean Late Shift Op.	Mean Total Op.
		300	10	56	4					
	Solution	205	10	54	3	716	602	1318	3.49	2.94
Minimum		200	10	54	0					

Figure 4.2: Aggregate Production Planner Using MS Excel & Open Solver

4.5 Conclusions

In this chapter, a model for the aggregate production planning of an airframe assembly line has been presented. It uses the information from the detailed scheduling model to build the yearly production plan as a sum of already calculated feasible short term schedules. By using that solutions, the planner can be sure that there is a feasible detailed schedule for the resulting plan. Before, that was not the case: not only the mid term planning was a more time consuming task but also there was a risk of not finding afterwards a feasible detailed schedule, needing to redo the whole planning and scheduling tasks.

The small size of the model has enabled its implementation using MS Excel and Open Solver. That is a great advantage for real deployment in the industry as it enables its use without further software installation or licenses. Moreover, the interface is a spreadsheet, easy to use for most of the production managers.

The model deals with some of the major characteristics identified for aggregate production planning problems. It takes into account all the parameters that were considered while doing this task manually. Nevertheless, most of its features could be modelled in more detail. For example, using the total number of operators as the sole objective function does not take into account the need of a minimum stable workforce. Neither does the model measure the difference between the minimum number of operators and the peak demand. That is an important information in a highly qualified industry such as the aeronautical, where it is not easy to find skilled operators.

As a result, an enhanced model is presented in the next chapter. In there, labor constraints are included in a more accurate way. Moreover, sustainability aspects are added. Those are two of the future research directions that were identified in the survey by [Cheraghalikhani et al., 2019] for aggregate production planning.

SUSTAINABLE MEDIUM TERM SCHEDULING

In this chapter I will go through the previous problem from a different perspective. Labor constraints and changeover costs will be modelled in a more realistic way. Moreover, I will take into account not only production costs but also energy costs and carbon footprint. As a result, the new model allows the production planner to select a yearly planning that prioritizes the use of less energy or minimizes the CO_2 emissions, even if they have a low impact in the total cost. As the use of self-consumption energy is increasing, it is also considered in the study. The importance of this approach in terms of cleaner production is twofold: on the one hand, it includes energy-conscious parameters in the planning process, which is usually done taking into account not more than production costs (such as inventory or personnel cost). On the other, the majority of the previous studies that take into account energy costs for other scheduling problems assume that the consumption of energy is constant during all the year, which is not the case in some regions where the temperature could vary more than 30 degrees from winter to summer. As in the previous chapter I will use real-based data from an aeronautic assembly plant in the south of Spain, especially suitable for the use of solar energy and influenced by different weather conditions throughout the year. The case study also reveals how cleaner production criteria can influence planning decisions and some guidance on the parameters that, with regards to our results, should be taken into account. If the automation trend continues, more energy will be used and less human labor. Consequently, this kind of approaches will be more relevant not only for the production costs but also for production sustainability and environmental impact.

The rest of the chapter is structured as follows: the first section provides a wider introduction and motivation of the study. Section 5.2 is dedicated to a detailed description of the problem. In Section 5.3 I present in depth the model's hypothesis together with the Linear Programming model that I have developed. That model has been solved following a set of objective functions.

In Section 5.4 I present the results of the real data experimentation. Finally, in Section 5.5, I summarize the main findings, and the impact that the implementation of the model would have.

5.1 Introduction

According with the World Health Organization [World Health Organization (WHO), 2016], more than 80% of people living in the urban areas are exposed to air quality levels that exceed the suggested limits. Energy production is among the most important source for this air pollution [International Energy Agency, 2016].

The industrial sector is responsible of 25% of the global European energy consumption [European Environment Agency, 2017], only out-ranked by the transport sector. As a result, there is a need for the industrial sector to shift from production cost oriented manufacturing to a cleaner perspective.

This swift of paradigm to a greener manufacturing will be encouraged by the rise in the electricity consumption. The US Energy Information Administration [U.S. Energy Inf. Adm., 2017] forecasts and increase in the demand of the electricity in residential, commercial, industrial and transportation sector, but the highest increase of the demand will be in the industrial sector. Following the same trend, in all possible scenarios but one the forecast price of energy for industrial use will rise in the USA from now to 2050 (see Figure 5.1).

The other cause that enhances the importance of green production in the future is the increase in process automation. As in other industries, the number of labor hours per aircraft is decreasing thanks to the advance automation technologies. This will result on higher energy consumption.

Due to all the prior reasons, there is a growing interest in taking into account the introduction of energy related parameters as part of the manufacturing decisions. Zhang et Hua [Zhang and Hua, 2007] studied the optimization of an oil refinery process flow for energy reduction. Wang et al [Wang et al., 2016a] do it for the touring process. Several authors have referred to detailed production scheduling under energy constraints. Lu et al [Lu et al., 2017] addressed energy efficiency in the case of a hybrid flow shop scheduling problem. Other authors have focused on energy costs. They have taken into account the generalized existence of energy time-of-use tariffs (TOU) and therefore worked on models that shift the demand from on-peak to off-peak periods. As an example, Shrouf et al [Shrouf et al., 2014] worked on the optimization of the production scheduling of a single machine to minimize total energy consumption costs and Che et al [Che et al., 2017], took into account parallel machines scheduling under TOU electricity tariffs.

However, minimizing the energy consumption does not always mean minimizing cost or emissions. Figure 5.2 represents the ton of CO_2 emitted per MWh each month of the year and their price in Spain [REE, 2017]. It can be observed that between months seven and eight the amount of CO_2 decreases slightly but, at the same time, energy price is the same. The contrary

Figure 5.1: Energy Price Estimation for the US Industrial Sector [U.S. Energy Inf. Adm., 2017]

happens in month 9, where a big increase in CO_2 emission is not followed by a so big increase in price. Zhang et al [Zhang et al., 2014] pointed out this trade-off between the two objectives. They studied it in detail for a flow shop scheduling problem using a multi-objective mixed-integer linear programming (MILP) model.

To my knowledge, all the references to energy-conscious scheduling deal with detailed production scheduling. Hence, Aggregate Production Planning problems had not yet been studied with this approach.

Another important characteristic of this enhanced model is that I will present a more realistic approach to labor costs. In the previous model, labor costs were considered directly proportional to the number of used operators per shift. In real production, plants, though, flexibility in the number of workers is limited. Hiring and layoff are not only costly but also may have an impact in labor's skills and consequently in product's quality [Silva et al., 2000]. As a result, in the new model there is a minimum number of workers that will be always hired, regardless the workload. Moreover, late shift has an extra cost with regards to early shift. To end with, the resource pool

Figure 5.2: Energy prices and emissions of CO_2 per MWh in Spain [REE, 2017].

for extra hours has also an upper limit, above which no more skilled workers are available.

5.2 Problem Description

I will take as a starting point the Aggregate Production Planning problem from the previous chapter. For the airframe assembly line, I have a set of 56 different production rates. Each production rate has a baseline schedule whose main characteristics are: cycle time, number of units per airframe type and cycle produced and number of operators per shift.

To take energy and CO_2 into account, four more elements are added to each production rate:

- **Energy usage.** Three different parts have been taken into account: the energy spent by the machines, the stand by energy whenever there is no production and the energy in morning and afternoon shifts if production is going on. Stand-by and machine energy are constant throughout the year. The energy consumption of the facility excluding the machines depends on the air conditioning and light hours. When the temperature exceeds

35 Celsius degrees maintaining a facility at 23 degrees requires plenty of energy. Keeping the temperature at 23 is not only important for the comfort of the employees but also for the quality assurance of some processes (for example, whenever carbon fiber is used, or for sealant curing process which are both present in the airframe assembly line).

Although the majority of the previous studies assume that the consumption of energy is constant in throughout the year, this is not the case in some regions where the temperature could vary more than 30 degrees. In Figure 5.3 the maximum, average and minimum temperature in the location of the assembly line are plotted. It can be seen that the difference between the highest and the lowest temperature in the year is of more than 35 degrees. In consequence, the energy consumed in the assembly line per shift varies depending on the outside weather.

- **Electricity Generation.** Electricity generation is increasingly focused at local level, since consumers become more engaged with their use because of the decrease in the price and the improvement of the efficiency of the electricity generators such as wind generators, solar panels, etc. [Electric Power Research Institute (EPRI), 2017]. In Spain, where the case study assembly line is located, up to 45.6% of the produced energy comes from renewable sources, 6.6% from solar energy in average. As it can be observed in Figure 5.4, the amount of energy generated varies a lot from winter to summer months. I have taken into account the use of solar panels to cover some of the assembly line electricity demand. A fixed amount of energy is considered to be produced per month. Due to energy storage constraints, energy can only be used during the same month it has been generated.
- **Energy Cost.** As it has been previously stated, electricity tariffs change through the year. For this case study, I have considered a constant energy prize per month.
- **CO₂ Emissions.** The amount of CO₂ emissions depends not only on the energy consumed but also on the technology that has been used for its production. That technology mix does not remain constant all the year round. That is the reason why CO₂ emissions per MWh vary (see Figure 5.2). In this case, I have used an average monthly value for CO₂ tons generated per MWh.

Due to the evolution of the energy parameters per month, the 56 detailed production schedules result on $12 \times 56 = 672$ different options.

Another main improvement of this model is the characterization of the labor cost. Before, only the number of operators was considered. Now, each production schedule is assigned a labor cost. That labor cost is calculated as the number of operators used per shift, multiplied by the days of cycle time and the operator cost per shift. This cost is different in each shift. Workers on the late shift are 10% more expensive than in the morning shift.

Figure 5.3: Mean Temperature Per Month in the Assembly Line's Location

Additionally, as several production rates are used during the year, there is a limited flexibility in the manpower size. In this airframe assembly line, changes between 7 and 12 operators per shift result on no extra cost, as within those limits, operators can be shifted to or from other assembly lines in the factory. If the total number of operators is less than 7, 60% of the salary must be paid to the not employed operators. If more than 12 operators are needed per day, each extra operator will have an extra cost of 60% because extra hours or new hiring will be needed. As an example, Table 5.1 shows the summary of the labor cost for the 8 schedules feasible for a cycle time of 4 days. Schedules are coded by a character chain including: Cycle time-ModelA Rate-ModelB Rate-Op Shift 1-Op Shift 2. It is important to remark that schedule 4-0-0-0-0 is a non-production schedule as closing the assembly line during some time period may be an option.

Another difference from the previous model is that in this case, the number of changeovers is not limited. Anyhow, changeovers are taken into account as an extra cost, contributing to the overall cost.

Figure 5.4: Solar Generation in Spain [REE, 2017]

Table 5.1: Feasible Schedules Depending on Jig Configuration for a 4-Day Cycle Time

Schedule Code	Cycle time	Variant A Rate	Variant B Rate	Morning Operators	Late Shift Operators	Total OP	Labor Cost
4-2-2-10-9	4	2	2	10	9	19	19280
4-4-0-10-10	4	4	0	10	10	20	20640
4-0-4-10-9	4	0	4	10	9	19	19280
4-2-0-5-5	4	2	0	5	5	10	8400
4-0-2-5-5	4	0	2	5	5	10	8400
4-2-0-10-0	4	2	0	10	0	10	8000
4-0-2-9-0	4	0	2	9	0	9	7200
4-0-0-0-0	4	0	0	0	0	0	3360

The outcome is still the selection of how many times to use each production rate while ensuring the deliveries and keeping the number of production changes and days within some given limits (Per month, a maximum and minimum number of days must be scheduled. There is also a maximum and minimum number of days to be scheduled per year).

In this case, I have used several objective functions. The comparison between them will allow to value the impact of taking energy-conscious parameters into account. The objective functions used are:

- **Cost related**

Energy Cost: Evaluates the cost of the energy bought in the assembly line. Hence, it takes into account that first, the generated solar energy is used and the remaining amount is bought.

Operator Cost: Evaluates the labor cost. As it was already explained, it takes into account that a minimum number of operators needs to be hired all the year and the difference between regular and extra hours.

Changeover Cost: Sums up the cost related to the changeover between production rates.

Total Cost Without CO_2 emissions: It is the sum of all the previous cost functions.

Total Cost With CO_2 emissions: It is the sum of the **Total Cost Without CO_2 emissions** and the price that would have to be paid for the CO_2 emissions if they were bought as extra emission coupons. Only CO_2 emissions related to the energy generation have been taken into account.

- **Energy Related**

Energy Used: Total MWh used in the assembly line, no matter the source (solar energy or bought).

CO_2 emissions: Total CO_2 emissions caused by the energy used. Only CO_2 emissions related to the energy generation have been taken into account.

- **Operator Related**

Maximum Number of Operators: It measures the peak number of operators. Although this is taken into account by the operator cost function, minimizing the peak number can have other non monetary advantages, such as more stable workforce, which can lead to higher quality and labor satisfaction.

The model has been solved using each of the objective functions in a mono-criteria approach.

5.3 Model Formulation

With all the previous requirements, a MILP model has been formulated. Its solution is an optimal set of schedules for the year, and can be calculated using all the set of objective functions.

The set months (**M**) has been added to the sets of the original model. All the sets are listed on Table 5.2. Moreover, new parameters and variables need to be added to the model. Table 5.3 contains all parameters. The first three groups are common to the previous model (operators, production and time) and the former two (energy and CO_2) are new. With regards to variables, Table 5.4 lists all of them. New variables are used for all the new cost functions calculation.

Table 5.2: Sustainable Medium Term Scheduling: Sets

O	Set of schedule options
M	Set of months of the year
S	Set of shifts
V	Set of product variants

Table 5.3: Sustainable Medium Term Scheduling: Parameters

Operators	OP_{so}	No. of operators used during shift $s \in S$ in Option $o \in O$
	OC_o	Operator cost per cycle in Option $o \in O$
Production	P_{vo}	No. of pieces of Variant $v \in V$ produced per cycle in Option $o \in O$
	D_v	Annual demand of pieces of Variant $v \in V$
	UC	Unitary changeover cost
	MC	Maximum number of changes allowed per year
Time	CT_o	Cycle time (in days) required for schedule Option $o \in O$
	UD	Maximum working days of the planning period
	LD	Minimum working days of the planning period
	UDM_m	Maximum working days to be used in month $m \in M$
	LDM_m	Minimum working days to be used in month $m \in M$
	IM_{mo}	1 if Option $o \in O$ belongs to month $m \in M$, 0 otherwise
Energy	E_o	MWh of energy used for a cycle time of Option $o \in O$
	EP_m	Energy price (€/MWh) during month $m \in M$
	DSG_m	Daily self-consumption of solar energy produced in month $m \in M$
CO₂	CO_{2m}	CO_2 ton generated in month $m \in M$ per MWh
	CP	CO_2 ton price

Table 5.4: Sustainable Medium Term Scheduling: Variables

Decision Variables	u_o	Number of times Option o is used
	α_o	1 if Option o is used, 0 otherwise
Auxiliary Variables	d_m	Number of days scheduled per month $m \in M$
	eb_m	Energy (MWh) bought during month $m \in M$
Obj. Funct.	o	Total operator working days used during the year
	mop	Max. no. operators per day scheduled through the year.
	co	Total operators' (labor) cost
	eu_m	Energy used (MWh) during month $m \in M$
	ss	Savings (in energy costs) due to solar panels energy generation
	ce	Yearly energy cost
	cc	Total changeovers' cost
	tc	Total cost ($oc + ce + cc - ss$)
	pCO_2	Total CO_2 tons produced
	cCO_2	Cost of CO_2 tons produced
	$tcCO_2$	Total Cost taking CO_2 tons emissions into account

The complete model is as follows:

$$\text{Minimize } z1 = tcCO_2 \quad (5.1)$$

$$\text{Minimize } z2 = tc \quad (5.2)$$

$$\text{Minimize } z3 = co \quad (5.3)$$

$$\text{Minimize } z4 = cc \quad (5.4)$$

$$\text{Minimize } z5 = ce \quad (5.5)$$

$$\text{Minimize } z6 = mop \quad (5.6)$$

$$\text{Minimize } z7 = \sum_m eb_m \quad (5.7)$$

$$\text{Minimize } z8 = ss \quad (5.8)$$

$$\text{Minimize } z9 = pCO_2 \quad (5.9)$$

Subject to:

$$\sum_o P_{vo} \times u_o \geq D_v \quad \forall v \in V \quad (5.10)$$

$$\sum_o u_o \times CT_o \times IM_{mo} = d_m \quad \forall m \in M \quad (5.11)$$

$$d_m \leq UDM_m \quad \forall m \in M \quad (5.12)$$

$$d_m \geq LDM_m \quad \forall m \in M \quad (5.13)$$

$$\sum_o CT_o \times u_o \leq UD \quad (5.14)$$

$$\sum_o CT_o \times u_o \geq LD \quad (5.15)$$

$$u_o \leq M \times \alpha_o \quad \forall o \in O \quad (5.16)$$

$$\sum_o \alpha_o \geq MC \quad (5.17)$$

$$UC \times \sum_o \alpha_o = cc \quad (5.18)$$

$$\sum_s \sum_o (OP_{so} \times CT_o \times u_o) = no \quad (5.19)$$

$$\sum_o (\sum_s OP_{so}) \times \alpha_o \leq mop \quad \forall o \in O \quad (5.20)$$

$$\sum_o (u_o \times OC_o) = co \quad (5.21)$$

$$\sum_o u_o \times EO \times IM_{mo} = ec_m \quad (5.22)$$

$$\sum_m d_m \times DSG_m \times EP_m = ss \quad (5.23)$$

$$ec_m - (DSG_m \times d_m) = eb_m \quad (5.24)$$

$$\sum_m eb_m \times EP_m = ce \quad (5.25)$$

$$\sum_m eb_m \times CO_{2m} = pCO_2 \quad (5.26)$$

$$(\sum_m eb_m \times CO_{2m}) \times CP = cCO_2 \quad (5.27)$$

$$oc + ec - ss + cc = tc \quad (5.28)$$

$$tcCO_2 = cCO_2 + tc \quad (5.29)$$

$$\alpha_o \in \{0, 1\}; u_o \in \mathbb{Z} \quad \forall o \in O \quad (5.30)$$

Total Yearly Production Constraints (5.10) ensure that the total number of units per variant (model) produced is enough to fulfil the yearly demand. No upper limit is fixed: some extra units can be produced and in practice, the number of units is bounded by the cost minimization.

Number of Days Scheduled Constraints (5.11) to (5.13) are linked to the number of really scheduled production days. Constraint (5.11) calculates the number of days used per month, constraints (5.12) and (5.13) make sure the number of days used is within the allowed interval for each month and constraints (5.14) and (5.15) do the same for the whole year or production period.

Number of Options Used The total number of options used is calculated in (5.16). It must not be bigger than the established limit per (5.17). Constraint (5.18) calculates the cost due to the scheduling option changeovers.

Number of Operators Constraints (5.19) to (5.21) deal with the number of operators used in the solution. (5.19) calculates the total number of operators needed and (5.20) the peak need of operators from all the scheduling options used. Finally, (5.21) stands for the total operator cost.

Energy Cost & Savings per Solar Energy Energy and savings due to solar energy are included in equations (5.22 to 5.25). Overall energy used is calculated in (5.22). Self-generation savings are stated in (5.23). The actual energy bought is calculated in (5.24) as the energy used minus the self-generation savings. Moreover, energy cost is calculated by (5.25).

CO_2 produced and associated cost To end with, the CO_2 produced is dealt with in constraint (5.26) and its cost in equation (5.27).

Overall Costs Two different costs are calculated. In (5.28), the total cost, tc , includes labor (co), change(cc) and energy costs (ec). It is the real cash out for the plant. In (5.29), the total cost with CO_2 , $tcCO_2$, is the result of adding to the total cost the equivalent CO_2 emissions' costs.

Objective Functions As for the objective functions, 9 different ones have been defined: equations (5.1) to (5.26). They deal with several approaches to the problem, depending on the parameter to be minimized. The first one, (5.28), minimizes the overall cost. Then, there are others that focus in only part of the cost: (5.21) minimizes only the labor cost, (5.18) the changeover cost and (5.25) the energy cost. In addition, objective function (5.20) minimizes the maximum number of operators in a day. On top of these, sustainability-focused objective functions have been defined: (5.22) minimizes the energy consumed and (5.23) the savings due to energy generated by the solar panels. Finally, CO_2 related objective functions are the minimization of the CO_2 emissions, (5.26), and the overall cost including CO_2 costs, (5.27).

Domain Constraints are (5.30).

5.4 Experimentation

Experimentation has been done using AIMMS [Roelofs and Bisschop, 2011] with CPLEX 12 under Windows 10 running on an Intel Core 7 with 16 GB of RAM.

The possible production rates have been the same 56 production rates from Chapter 4. For each month, there is a different energy consumption per shift. They are presented in Table 5.5. Moreover, Table 5.6 shows for each month the energy price per MWh, the tons of CO_2 generated per MWh and the expected MWh to be generated by solar energy. Those data are based on information from *Red Eléctrica*, the transmission agent and operator of the Spanish electricity system [REE, 2017]. Carbon emission price per ton was set to 5€ (real price of future market emission price by December 2017 [CO_2 Price, 2017]).

Table 5.5: Energy Used per Shift and Month (MWh)

	M01	M02	M03	M04	M05	M06	M07	M08	M09	M10	M11	M12
Energy for Machines	340	340	340	340	340	340	340	340	340	340	340	340
Energy Morning Shift	297	467	807	985	1293	1571	1702	1378	1471	891	571	380
Energy Late Shift	327	514	887	1084	1422	1728	1872	1516	1618	981	628	418
Stand-by Night	30	30	30	30	30	30	30	30	30	30	30	30
Stand By Late Shift and Night	60	60	60	60	60	60	60	60	60	60	60	60
Stand By Full Day	90	90	90	90	90	90	90	90	90	90	90	90

Table 5.6: Energy Prices, CO_2 Generation and Solar Energy Generation per Month

	M01	M02	M03	M04	M05	M06	M07	M08	M09	M10	M11	M12
€/ MWh	47.42	38.12	37.69	33.43	35.57	46.7	48.17	48.12	51.09	61.19	63.91	69.06
t CO_2 / MWh	0.21	0.17	0.16	0.13	0.15	0.21	0.27	0.26	0.32	0.33	0.33	0.36
Solar E. Generation (MWh)	1.7	2.3	3.1	3.4	4	4.5	4	4.1	3.6	2.7	2	1.7

The number of airframes to produce was set to 50 units of airframe A and 80 of airframe B. Moreover, the scheduled days per month had to be between 240 and 230 per year and from 19 to 23 per month. The unitary change cost is 400 €.

That data set has been solved with the 9 objective functions explained in Section 5.3. Those objective functions represent the point of view that different stakeholders may have whenever approaching the problem. People in charge of production will usually focus in minimizing the *labor cost*, *changeover cost* or the sum of both. On the other side, HHRR managers will be concerned about the *maximum number of operators* needed.

Finally, environmental issues are rarely taken into account. If they are included, the most straightforward way is to add the cost, which I have done in the *Total Cost* objective function (labor cost, energy cost and changeover cost) and the *Total cost with CO_2* , that adds also the equivalent cost of the CO_2 emissions. However, the energy used is not always correlated with the energy cost. Therefore I have also included the *Used Energy* and the *CO_2 emissions* reduction as

Figure 5.5: Energy Used Result per Objective Function

additional objective functions. Finally, the maximization of the *savings coming from the solar panels* has been added, as it might be also a criteria in order to ensure or evaluate the efficiency of that installation.

To begin with, I will review the results of the different functions in terms of energy and CO_2 emissions. Figure 5.5 shows the energy used in the solutions provided by each objective function, ordered from lowest to highest. Optimizing the total MWh used results on savings of up to 40% compared to the option that most energy uses. Also, it is important to say that the difference between minimizing the energy used and the energy cost is less than 10 MWh per Year (4%).

In Figure 5.6 I have added to the previous bar plot the CO_2 emissions per solution. I had envisaged that those two would not be strictly correlated. In fact, it is true that on the options with less energy used, minimizing CO_2 results on 10% more MWh per year. On the other side, minimizing the energy implies a 10% more CO_2 . However, the option with CO_2 minimization still provides 54% reduction on the MWh used and a 62% reduction of CO_2 emissions (compared with the worst option: changeover cost reduction).

Figure 5.6: Energy Used and CO_2 Emissions Result per Objective Function

Nevertheless, it would be too naive to think that the energy used or CO_2 emissions can be the only driver for a planning decision. In consequence, Figure 5.7 combines the information on the three main variables at a time: Energy cost (y axis), Total Cost with CO_2 (x axis) and CO_2 emissions (balloons' size). Dominated solutions are displayed in grey and not dominated solutions in green. Table 5.7 includes the information related to the extra percentage per parameter for each objective function.

Some objective functions perform badly in both total cost and energy usage. For example, focusing on the changeover cost results on bad results for both. That is a relevant remark as using a constant production rate for the year would lead to that solution, which is 20% more expensive and uses 140% more energy than the best solution of each. Also, it is the option with the highest CO_2 emissions.

As for the use of solar energy, between 7 and 17% of the total energy used comes from these source, depending on the solution. Therefore, it turns out to be worth using it. However, maximizing the savings produced by it leads to a solution with a 26% extra cost and 93% more

Figure 5.7: Energy Used, CO_2 Emissions and Cost per Objective Function

Table 5.7: Performance in Energy, Cost and CO_2 per Objective Function

(Compared to the best in class)

	Used Energy	CO_2 Emissions	Total Cost
Used Energy	0,00%	12,00%	38,00%
Energy Cost	4,00%	1,00%	36,00%
CO_2 Cost	11,00%	0,00%	35,00%
CO_2 Emissions	11,00%	0,00%	38,00%
Total Cost	51,00%	64,00%	0,00%
Total Cost + CO_2	51,00%	64,00%	0,00%
Max No. Operators	81,00%	98,00%	8,00%
Labor Cost	86,00%	103,00%	2,00%
Solar Energy Savings	93,00%	107,00%	26,00%
Changeover Cost	140,00%	163,00%	20,00%

energy usage.

Another objective function that is dominated is minimizing the maximum number of operators. It is outperformed both in energy used and cost by the two other labor related objective functions: reducing the labor cost and the total number of operators. Among those two, both lead to nearly the same cost, but reducing the labor cost is a more efficient solution in terms of energy (3% savings).

On top of these, the CO_2 emission cost is so little compared to the other operating costs (it is three orders of magnitude less than the total cost) that minimizing the cost taking the emission costs into account or without them leads to the same solution.

To sum up: given all the objective functions, minimizing the total cost (including energy costs) seems to be a good compromise solution. However, it results on a 51% increase in the energy used and 64% in the CO_2 emissions. On the other side, minimizing the energy has an impact of 38% extra cost. In a real production scenario, it will be suitable to make a more in detail study of the Pareto Front between those two objectives, as the best solution will be somewhere in that front.

5.5 Conclusions

In this chapter, I have introduced sustainability characteristics in the aggregate production planning problem for the airframe assembly line. It takes into account energy-related parameters and CO_2 emissions. To my knowledge, energy costs and usage had not been included before in this genre of decision.

I have solved the model using a set of objective functions that represent the aims of the main stakeholders that may be involved in a production line. This objective functions include minimizing the total cost, minimizing only labor or only changeover costs. Another objective functions focus on energy usage and CO_2 emissions.

In a next step, I have compared the solutions obtained by the different objective functions. I have proofed that the more traditional approach of minimizing the cost leads to environmentally non-efficient solutions. Nevertheless, focusing only on energy cost or usage minimization can result on too costly solutions that may not be possible for the industry. However, a further study of the Pareto front between energy usage and the total cost, would find the intermediate solutions that can be good enough in both total cost and energy usage.

Another relevant conclusion is the importance of taking into account not only the energy cost but also the amount of energy used. In our case, reducing only the cost lead to a solution which used a 4% more of energy than the most efficient one.

At the same time, I have taken into account the impact of CO_2 emissions in the model. Using fewer energy does not always mean that there will be less impact on the environment. In this case, reducing only the energy usage leads to 12% more CO_2 emissions than in the lowest emission solution. Moreover, with the current prices of CO_2 , taking into account the emissions bonus'

price does not vary the solution. The CO_2 ton bonus price should be much higher to have a real impact on total cost, at least in this kind of industry.

I believe the contribution of an aggregate production planning model including energy usage as a decision variable is especially relevant to ensure a swift to a greener production. Other two factors that will increase the importance of this genre of approaches in the near future are the current trend of increasing electricity prices and the higher automation that will decrease the percentage of labor cost with respect to energy cost. Further research can extend this approach to other scheduling steps, taking into account, for example TOU tariffs that may imply a different energy cost within a day and not only from one month to another.

CONCLUSIONS

In this part I have worked on the medium term scheduling for the airframe assembly lines. No previous references had been found of this problem in the aeronautical industry. However, in the general planning and scheduling literature, it belongs to aggregate production planning problems. Those genre of problems have been studied for long. Buffa and Miller set the basis of aggregate production planning in 1979 [Buffa and Miller, 1979]. A major literature review was published in 1992 by [Nam and Logendran, 1992] and has been very recently updated by [Cheraghalikhani et al., 2019].

In a first approach, I developed a model that provides a fast solution to the aggregate production planning problem as it was solved up to now. That model takes into account the possible short term scheduling production rates calculated from the model in Part II. Using them as input data, it looks for a set of short term schedules that complies with the expected production rate in the available production time. Its objective is to minimize the overall number of operators used. The resulting MILP model has been implemented in a MS Excel-Sheet using Open Solver. Thanks to that straightforward implementation, that model is an important asset for the shop floor: it can be directly used by production managers with no need of additional software nor training. At the same time, it has encouraged the production teams to also use the short term scheduling model.

Per contra, from the academical point of view, that first aggregate production planning model ignores several relevant aspects of the real problem. As an example, it assumes that changes in the workforce are unlimited or does not take into account changeover costs. For this reason, another enhanced model has been deployed. It includes more realistic modelling of human labor, its cost and hiring and layoff limits. Moreover, sustainability conscious parameters have been added. To my knowledge and according to the latest review by [Cheraghalikhani et al., 2019], no

other authors had taken energy into account in aggregate production planning problems. Hence, I have modelled the differences in energy cost and consumption over the year. This differences had addressed in the energy-related manufacturing literature either. To end with, CO_2 emissions have been also included in my study.

In conclusion, the contribution of this chapter is fourfold: the first model is a major asset for boosting the implementation of scheduling models in the aeronautical airframe assembly line under study. It proofs that sometimes the smaller models can lead to relevant transformation in real operations. Additionally, the second model provides a more in detail approach to labor costs. Moreover, the use of a set of different objective functions is more adequate to the actual manufacturing environment. Last but not least, sustainability criteria are addressed for the first time in aggregate production planning. The way I have taken energy into account fills a gap not only in this planning area, but also in others, as cost and consumption variability have rarely been considered.

Part IV

Short Term Scheduling for Final Assembly Lines: Resource Constraint Scheduling Problems

This part is dedicated to the next step on the supply chain: final assembly lines. Within this production step, it deals with the short term scheduling problem. That is, the red-coloured area from figure IV.1 As it was said in Chapter 2, this problem belongs to Resource Constraint Scheduling Problems.

Figure IV.1: Aeronautical Planning and Scheduling Matrix - RCSP

The structure of this part is as follows: Section 7.1 describes the case study of short term scheduling in a station of an aeronautical final assembly line. As in the previous parts, the input data and the scheduling requirements are analysed in detail. Afterwards, Section 7.2, is dedicated a literature review on the more general Resource Constraint Scheduling Problem. As a result, I chose to use an event-based MILP model for this case study. The model I developed is presented in Section 7.3 and the experimentation results in Section 7.4. To end with, final conclusions and proposals for further research directions are presented in Section 7.5.

FINAL ASSEMBLY LINE SHORT TERM SCHEDULING

7.1 Problem Description

As it has been explained on Chapter 2, aeronautical assembly lines consist on a series of stations where different works are executed. Each product has to go through all the stations. At the same time, in most cases the line is synchronised, this means that the time that each product remains on a station is always the same and equal to the rate at which the assembly line produces its output.

Usually, both final and intermediate assembly lines are dedicated to only one product family. However, there may be some specific installations between the products of a same family. In that case, an effort is made in order to guarantee that the cycle time remains standard throughout the line. Different strategies for that, referred to the aeronautical industry, can be found in [Heike et al., 2001].

The assignment of the works to a station is in most of the cases related to industrial issues: assembly technologies and the need of specific jigs that cannot be easily moved. Therefore, the assignment of works between stations is made only once, during the line definition. Although there may be a small percentage of works that can be done in more than one station, once the works are assigned they are rarely moved from one station to another, it can be assumed with no loss of generality that the task assignment per station is fixed.

Considering all these, the scheduling decision consists on **establishing the order in which the works will be done together with the resources allocated to each of them, given the station's cycle time and a set of works per station**. The result is usually displayed as a bar chart where each task is assigned a start / end date and a set of operators. Other times, a performance tracker view is used. The main difference is that the performance tracker is

CHAPTER 7. FINAL ASSEMBLY LINE SHORT TERM SCHEDULING

worker-oriented, so each line provides information on the task to be performed by an operator all through the cycle time. An example of each of them is presented in Figures 7.1 and 7.2.

Figure 7.1: Bar chart Example

Performance Tracker					
Shift Number			Shift 1	Shift 2	Shift 3
Real Date			Sept 13, 2019	Sept 16, 2019	Sept 17, 2019
Shift			1st	1st	1st
Specialization (SGM / Workstation in the workorder)	Description				
8225-51 - 1		STD	6 8 12	12 15 17	17 20
		REAL			
8225-51 - 2		STD	3 5	5 7 10 14	14 16 18
		REAL			
8225-51 - 3		STD	6 8 12	12 15 17	17 20
		REAL			
8225-51 - 4		STD	3 5	5 7 10 14	14 16 18
		REAL			
HNC					
ALERTS					
INCIDENTS	Register				
	Report No. OP. & Type: F, P, Q, I, M				
MILESTONES OF TESTING					

Figure 7.2: Performance Tracker Example

In the recent years, automation of aeronautical stations has experienced major improvements. In spite of this, aeronautical assembly remains intensive in highly-qualified operators. Often, some of the works need to be done by workers with a specific certification, and not all them have the same certifications. These different skills are managed by the use of profiles that gather one or more certifications. Each operator is assigned a profile, according to his skills. As well as this, each task may be done by operators with one or several profiles. For example, if *profile 1* includes only elementary mechanical tasks (such as drilling and riveting) and *profile 2* includes the previous ones and also pipes installation, a work involving riveting and drilling can be done by both profiles.

Operators are organized in permanent groups, with a team leader per group of 5 to 15 operators. Each group is responsible of tracking its performance and taking corrective actions. In order to enable this, each group works together and is assigned to a station for the whole cycle

time. Extra resources may be available for peak demands, but they must not be included on the standard schedule. As a result, if n operators are needed only one day at one station, they will stay in the station during all the cycle time, and the related cost must be allocated to that station.

Some of the assembly works can be performed by only one operator, whereas others must be done by two or more. On some cases, there is a range of possible operator numbers, which will lead to a set of production times for the work. As well as this, having more than the minimum number of operators reduces the lead time, but not in a linear way, as some activities may not be performed in parallel. For example: the lead time for preparing the necessary material and reading the documentation will be the same no matter the number of operators working. As a result, the number of operators reduces the lead time in a non-linear manner specific per work. When several operators are involved, they all need to have the same profile.

Stations can be of very different sizes: from a part of a major component (a wing, for example) of 1-10 meters, to a complete aircraft (hundreds of meters) in the last steps of a final assembly line. However, even the smallest stations are big enough for two or more jobs to be performed in parallel. Usually, several tasks are to be done near to each other, in a way that they cannot be executed at the same time due to space limitations. As a result, stations are divided on smaller working areas, where a limited number of operators can work at a time. In consequence, the space on each area is a scarce renewable resource for scheduling.

Each task may require a set of tools that can be standard or specific for the work. If they are specific, different works rarely share a tool and if they share it, the tool can be duplicated if works are to be performed in parallel. Standard tools are available so that all operators can use them freely. Therefore, tools need not be included in the scheduling model.

The constraints between tasks can be of different nature. The most common case is that of precedence constraints: when a task cannot be started until a previous one has been finished. For example: harnesses cannot be routed until the supports to which they are attached have been riveted to the aircraft structure, or a functional test cannot be performed until the system it tests has been completely installed.

Another kind are non-parallel constraints: these mean that some activities can be done in any order as far as they are not being performed at the same time. This is the case of some tasks that due to health and security reasons must be done with as fewer persons as possible in the hangar, e.g. corrosion inhibition application. This also happens in tests that require a specific aircraft condition: hydraulic tests need to have the power on, but the aircraft must have its power off for fuel tests.

Finally, maximum and minimum time lags also occur. For example, after sealing some part of the aircraft, the sealant must cure and therefore no work must be done near it until some time after the end of the task. Bonding tests have to be performed at the end of the installations, and bonding protection must be accomplished within the same working day where the test was passed. In some cases, not only a maximal time lag but also the same working team is required.

In accordance with the fixed cycle time, the objective function will be to minimize the resource consumption per station. As I have said, this is equivalent to minimizing the sum of the peak operators demand per profile.

On average, for final assembly lines, the cycle time varies from 14 to 25 working days. There are two or three operator teams per station, that is, more or less 20 operators in shifts of 8 hours. The most common profiles are: mechanical technician, electrical technician, fluid systems technician, inspector and test specialist. However, as works within a station are usually from similar technologies more than three profiles are rarely required per station. As for the working areas, there can be defined up to 5 different ones per station. The total workload is in most cases between 1000 and 3000 manhours.

Precedence constraints are the most frequent. There are normally a small percentage of works that do not have any kind of precedence relationship with the others. Works are usually organized on several groups (1-10) that can be done in parallel. Within this groups, most of the task must be done in series. Non-parallel constraints and maximal time lags occur at a much lower rate than precedence constraints but, at the same time, they can not be omitted because they have a major impact on product quality, reliability or health and safety issues.

In summary, the short term scheduling of a final assembly line station must fulfil the following requirements:

Cycle time

- All the tasks must be completed within the stations' cycle time.

Objective function: number of operators

- Given a fixed cycle time, the aim is to find a schedule that minimizes the number of operators needed.

Station areas definition

- The station is divided in working areas and each operation is assigned to one of those working areas.

Task definition

- Each task can be performed in different modes. Each mode is characterized by a number and profile of operators.
- Each task can be performed by one or several operator profiles. However, all the operators selected to do the task must belong to the same profile.
- The workload of the task depends on the number of operators assigned and therefore on the selected execution mode.

- Whenever a task begins, an execution mode is selected. The same mode must be use through all its execution.
- No preemption is allowed: once a task begins it must be continued until it is finished.

Constraints

- The number of operators working on an area at a specific time must be lower than the capacity of that area.
- There are precedence constraints between some operations.
- The precedence constraints between operations may also include maximal or minimal time lags.
- There are non-parallel constraints between some operations: those operations cannot be active at the same time.

Given this problem description, the next section will be dedicated to the review of similar problems in the literature.

7.2 Literature Review

The problem described on the previous chapter is similar to a project scheduling problem. As a first approach, a project scheduling problem consists on a time window and resource assignment for a set activities of known duration and resource requests, that must be executed guaranteeing some precedence relations.

Resources can only be assigned to one task at a time. Hence limited resources may impose additional precedence relations between activities consuming the same resource, thereby possibly increasing the project duration. At the same time, carrying out activities simultaneously in order to save time will usually result in higher costs in terms of resource consumption.

These considerations lead to the following optimization problems:

- **RCSP - Resource Constrained Scheduling Problem:** Given constant limits for the available amount per resource, its objective is to find the shortest possible project duration.
- **TCSP - Time Constrained Scheduling Problem:** Given a time limit for the project duration the objective is to find the least resource consuming schedule, if resources are assumed to be available in unlimited amounts at a fixed cost.

However, the TCSP can be considered a variant of the RCSP. Although some authors have referred to them separately, [Mohring, 1984] already established the parallelism between them in 1984.

Using the RCSP definition by Artigues [Artigues et al., 2010a], both scheduling problems are combinatorial optimization problem defined by a 6-tuple $(W, p, A, K, B, b(lt))$, where:

- W is a set of activities.
- p is a vector of processing times per activity.
- A is the set of temporal constraints.
- R is the set of resources.
- B stands for the demand matrix (resource consumption per activity).
- b is the resource capacity vector - For the RCSP.
- lt is the lead time capacity vector - For the TCSP.

The objective is to identify a feasible schedule, which assigns a start / completion time (S_i/F_i) to each activity as well as a resource allocation, taking into account the temporal constraints and minimizing the total project lead time (RCSP) or the resource consumption (TCSP).

Although in practice deadlines often occur in projects, the Time Constrained Project Scheduling has been considered only rarely in the literature. On most of the cases, it has been considered combined with resource constraints, as is the case of scheduling with resource constraints and time windows.

On the rest of the chapter, I will use the term RCSP to refer to the more general case of scheduling problems, in order to use the same notation from the literature. Nevertheless, the conclusions and discussions are valid for the TCSP.

Until 1999, there was not a common notation for RCSP. Brucker [Brucker et al., 1999] proposed one based on the extension of the $\alpha|\beta|\gamma$ generalized scheme for the machine scheduling and resource constrained machine scheduling literature [Graham et al., 1979], already used in Chapter 3.2. In this notation, α refers to the resource environment, β to the activity characteristics and γ to the objective function.

Using that notation, the short term scheduling of aeronautical final assembly line stations can be classified as:

$$MPS_{m,\sigma,\rho} \mid prec,temp,LT \mid \sum C_o * num_o^{op}$$

- $\alpha = MPS_{m,\sigma,\rho}$. This stands for a multimode resource constraint project where each activity can be processed in several alternative modes and there exists a set of renewable resources available for each time period during the project execution: m being the resources, σ the units of each resource available and ρ the maximum number of units of the resources demanded by an activity. For this particular problem, the activities are the work tasks assigned to each station. The renewable resources are the number of operators (each of

them belonging to a profile) and the space in each of the station's working areas. As well as this, each mode for an activity defines a combination of operator profile, number of operators and duration. All the operators assigned to an activity must be from the same profile and the range of possible numbers of allocated operators per tasks is independent from the chosen profile.

- $\beta = temp$. The set of temporal constraints includes different types. There are precedence constraints (task w' can not start until task w has been completed), non-parallel constraints (tasks w and w' cannot be in progress at the same time, but there is no precedence relation between them), and maximal time lags between tasks (task w' must start within a maximal time after w has been completed). All the temporal constraints are independent from the mode in which a task is executed. As for the specific case of tasks that must be done by the same team and with a maximum delay between them will be treated by pre-processing the data and transforming them into a single work, and therefore they are not included in the model.
- $\gamma = \sum C_o * num_o^{op}$. The objective function is to minimize the resource investment. The total lead time is fixed by the assembly line cycle time. In consequence, the objective function is to minimize the labor cost of the assembly. As the operators once assigned to a station stay working on it for all the cycle time, minimizing the labor cost is equivalent to minimizing the maximum number of operators needed throughout the cycle time. I will consider that the cost of an operator does not depend on its profile.

7.2.1 Solution Methods for the RCSP

Being the RCSP a NP-Hard problem, instances with more than 60 activities have been up to now difficult to solve using exact methods. Therefore, a wide range of both heuristic and metaheuristic methods have been proposed. In this Section, I will provide an overview of some of the proposals.

On 1963, Kelley [Kelley, 1963] published a first schedule generation heuristic. Since then, a large number of different solution techniques have been proposed. The core of most of them are Schedule Generation Schemes (SGS). In some cases, the schedule generation is enhanced by the use of priority rules, giving birth to a set of heuristics known as priority based RCSP heuristics. Priority rules can focus on different activity characteristics. The main groups are activity-based, network-based, critical path-based or resource-based rules. Table 7.1 summarizes some of the existing priority rules.

Priority-based heuristics are often used in practice since they have small running times and are easy to implement. Furthermore, they are often used to calculate lower/upper bounds or initial solutions.

Kolisch and Hartman [Kolisch and Hartmann, 1999] published in 1999 a detailed review of heuristics for the resource constraint scheduling problem and their computational analysis. They

Table 7.1: Existing Priority Rules for RCSP Heuristics

[Brucker and Knust, 2011]

Type	Rule	Chooses the activity with the:
Activity-based	SPT	Smallest processing time
Activity-based	LPT	Longest processing time
Network-based	MIS	Most immediate successors
Network-based	LIS	Least immediate successors
Network-based	MTS	Most total successors
Network-based	LTS	Least total successors
Network-based	GRPW	Greatest rank positional weight
Critical path-based	EST	Smallest earliest starting time
Critical path-based	ECT	Smallest earliest completion time
Critical path-based	LST	Smallest latest starting time
Critical path-based	LCT	Smallest latest completion time
Critical path-based	MSLK	Minimum slack
Resource-based	GRR	Greatest resource requirements

have updated it in 2006 [Kolisch and Hartmann, 2006].

Metaheuristics are also widely spread as solution methods for this problem. The most common are genetic algorithms, tabu search, simulated annealing and ant colony systems. Hartman proposed a genetic algorithm in [Hartmann, 1998] which was improved by Valls et al in [Valls et al., 2003]. Examples of tabu search algorithms have been published by Artigues [Artigues et al., 2003], Klein [Klein, 2000] and Nonobe and Ibaraki [K. Nonobe, 2002]. To end with, ant colony optimization approaches were first used by Merkle et al. [D. Merkle, 6]. More recent applications can be seen in [Thiruvady et al., 2016] and [Myszkowski et al., 2015].

For a more detailed description of several heuristics and metaheuristic methods for solving the RCSP, including computational results, reviews from Hartman and Kolisch may be consulted: [Hartmann and Kolisch, 2000] and [Kolisch and Hartmann, 2006].

Constraint Programming has also proven to be a very efficient method for solving scheduling problems. The basic idea in constraint programming is that the user states the constraints and a general purpose constraint solver is used to solve them. [Rossi et al., 2006]. Baptiste et al. went through scheduling applications of Constraint Programming in [Baptiste et al., 2006]. In addition, Sitek and Witarek [Sitek and Wikarek, 2016] presented a constraint-based approach combining OR and CP and applied it to the more general RCSP. Artigues used it in 2013 for a multi-mode resource-constrained multi-project scheduling problem, combined with a MIP relaxation and Large Neighbourhood search [Artigues and Hébrard, 2013]. Moreover, [Arkhipov et al., 2018] used it for the resource assignment in an aircraft assembly line using economic and ergonomic constraints. As Artigues, they also used CP combined with Mixed Integer Linear Programming. In consequence, the next subsection is dedicated to MILP formulations for the RCSP.

7.2.2 MILP Formulations for the RCSP

Although up to now only small instances can be solved to optimality by mixed integer linear programming (MILP) methods, they are often useful when combined with others in hybrid methods. In fact, most of the best known lower bounds for some common instance sets were obtained by an hybrid method including constraint propagation and MILP formulations. Moreover, in the recent years, more efficient MILP solutions are being presented and therefore this formulations are becoming more promising.

They exist a large number of MILP formulations for the general RCSP. These formulations can be divided on three main groups: Discrete Time Formulations, Continuous Time Formulations and Event Based Formulations.

As a common notation, valid for all of the formulations, we must remember that a feasible schedule will be one that assigns for each task a start time that is feasible given the precedence constraints (7.1) and the resource constraints (7.2).

$$s_{w'} - s_w \geq p_w \quad \forall (w, w') \in A \quad (7.1)$$

$$\sum_{w \in W_t} b_{wk} \leq B_k \quad \forall k \in R, \quad \forall t \in T \quad (7.2)$$

Where s_w is the starting time of task w , and A stands for the precedence relations graph between activities ($(w, w') \in A$ if w must precede w'). As well as this, W_t represents the set of activities in process at time t . B_k is the total available quantity of the renewable resource $k \in R$ and b_{wk} is the resource demand of type k for activity w .

7.2.2.1 Discrete Time Formulations

In discrete time formulations, the time horizon T is divided into time slots $[t-1, t]$ for $t = (1, \dots, T)$. The basic discrete time formulation (DT) was proposed by Pritsker [Pritsker et al., 1969]. He defined a time-indexed binary variable x_{wt} , where $x_{wt} = 1$ if activity w starts at time slot t and zero otherwise. As well as this, activity $n+1$ is the dummy activity for the end of the project.

Minimize:

$$z = \sum_{t=0}^T t x_{n+1,t} \quad (7.3)$$

Subject to:

$$\sum_{t=0}^T x_{wt} = 1 \quad \forall w \in W \quad (7.4)$$

$$\sum_{t=0}^T tx_{w't} - \sum_{t=0}^T tx_{wt} \geq p_w \quad \forall (w, w') \in A \quad (7.5)$$

$$\sum_{w=1}^n b_{wk} - \sum_{\tau=\max\{0, t-p_w+1\}}^t x_{w\tau} \leq B_k \quad \forall t \in (0, T-1) \quad \forall k \in R \quad (7.6)$$

$$x_{wt} \in \{0, 1\} \quad \forall w \in W, t \in (0, T) \quad (7.7)$$

Where equation (7.3) is the objective: to minimize the project completion time. Constraint (7.4) ensures that each activity is programmed once and only once. Precedence relations are satisfied as per constraint (7.5). The resource constraints are guaranteed by (7.6), since an activity w is only being processed in the interval $[t, t+1]$ if and only if its starting time is in the interval $[t-p_w+1, t]$.

This formulation consists of $O(nT)$ binary variables and $O(|E| + |R|T + n)$ constraints. The number of variables can be reduced if time windows are defined per activity, by the calculation of its earliest / latest start time. In that case, it would be defined that $x_{wt} = 0 \quad \forall t \in (0, ES_w) \cup (LS_w, T)$ and the number of variables would be $\sum_{w=1}^{n+1} (LS_w - ES_w)$.

After Pritsker, Christofides ([Christofides et al., 1987]) proposed the Disaggregated Discrete Time formulation (DDT). This formulation replaces the precedence constraints (7.5) by a new set (7.8). On the one hand, it implies a larger number of constraints but, on the other hand, is a tighter formulation and therefore its linear relaxation provides a better lower bound.

$$\sum_{\tau=t}^T x_{w\tau} + \sum_{\tau=0}^{\min\{t+p_w-1, T\}} x_{w'\tau} \leq 1 \quad \forall (w, w') \in A, t \in (0, T-1) \quad (7.8)$$

The main drawback of both discrete time formulations is the increase in the number of variables as the time horizon grows.

7.2.2.2 Continuous Time Formulations

In this formulations, the continuous variable s_w is used to represent the starting time of activity w . A set of binary variables $x_{ww'}$ is used for the precedence constraints, where $x_{ww'} = 1$ if activity w' cannot start until activity w is completed and 0 otherwise. This formulations are similar to some of the ones used for the Traveling Salesman Problem (TSP).

Forbidden Sets Formulation (FS) Alvarez-Valdés and Tamarit proposed a formulation based on the definition of forbidden sets [Alvarez-Valdés and Tamarit, 1993]. A forbidden set is a subset of activities $F \subset W$ if between its activities there are no precedence constraints but they cannot be processed in parallel due to the resource constraints. That is:

- $x_{ww'} = 0 \ \forall (w, w') \in F$
- $\exists k \in R \mid \sum_{w \in F} b_{wk} \geq B_k$

A forbidden set F is a minimal forbidden set if neither of its subsets is a forbidden set itself ($\forall F' \subset F, \sum_{w \in F'} b_{wk} \leq B_k$). Feasible schedules are obtained by breaking all the minimal forbidden sets, that is, including a new precedence relation between at least two of its activities in order to comply with the resource constraints. Being F the set of minimal forbidden sets, the complete FS formulation is:

Minimize:

$$z = s_{n+1} \quad (7.9)$$

Subject to:

$$x_{ww'} + x_{w'w} \leq 1 \ \forall (w, w') \in W, w < w' \quad (7.10)$$

$$x_{ww'} + x_{w'w''} - x_{ww''} \leq 1 \ \forall (w, w', w'') \in W \quad (7.11)$$

$$x_{ww'} = 1 \ \forall (w, w') \in A \quad (7.12)$$

$$s_{w'} - s_w - Mx_{ww'} \geq p_w - M \ \forall (w, w') \in W \quad (7.13)$$

$$\sum_{(w, w') \in F} x_{ww'} \geq 1 \ \forall F \in F \quad (7.14)$$

$$x_{ww'} \in \{0, 1\} \quad (7.15)$$

$$s_w \geq 0 \ \forall w \in W \quad (7.16)$$

M is a big enough number, that can be set to an upper bound of the project makespan (for example, $\sum_w p_w$). The objective function value is obtained directly by the starting time of the dummy final activity. Constraints (7.10) and (7.11) prevent the cycles on the sequencing of the activities. The precedence constraints are covered by (7.12). The link between variables $x_{ww'}$ and the activities starting time is made by (7.13). Finally, the minimal forbidden sets are broken by (7.14), as at least one sequencing decision must be taken per minimal forbidden set. Constraints (7.15) and (7.16) are domain restrictions.

This formulation has $O(n^2 + n)$ variables and $O(2^n |n^3|)$ constraints. Due to the exponential growth of the number of constraints and the difficulties in identifying the minimal forbidden sets, this formulation is barely used in practice.

Flow-Based Continuous Time Formulation (FCT) Described by Artigues, it shares with the previous formulation the use of the starting times s_w and sequencing $x_{ww'}$ variables. However, instead of forbidden sets, it uses a continuous variable $f_{ww'k} = (0, 1 \dots B_k)$ to represent the quantity of resource k that is transferred from activity w (at the end of its processing) to activity w' (at the

start of its processing). It sets the dummy start activity as a resource source and the end activity as a sink ($b_{0k} = b_{n+1k} = B_k$). [Artigues et al., 2003]

Minimize

$$z = s_{n+1} \quad (7.17)$$

Subject to:

$$x_{ww'} + x_{w'w} \leq 1 \quad \forall (w, w') \in W, w < w' \quad (7.18)$$

$$x_{ww'} + x_{w'w''} - x_{ww''} \leq 1 \quad \forall (w, w', w'') \in W \quad (7.19)$$

$$x_{ww'} = 1 \quad \forall (w, w') \in A \quad (7.20)$$

$$s_{w'} - s_w - Mx_{ww'} \geq p_w - M \quad \forall (w, w') \in W \quad (7.21)$$

$$f_{ww'k} - \min\{b_{wk}, b_{w'k}\}x_{ww'} \leq 0$$

$$\forall w \in W - \{n+1\}; w' \in W - \{0\}, k \in R \quad (7.22)$$

$$\sum_{w'=0}^{n+1} f_{ww'k} = b_{wk} \quad \forall w \in W, k \in B \quad (7.23)$$

$$\sum_{w'=0}^{n+1} f_{w'wk} = b_{wk} \quad \forall w \in W, k \in B \quad (7.24)$$

$$f_{n+1,0,k} = B_k \quad (7.25)$$

$$x_{ww'} \in \{0, 1\} \quad (7.26)$$

$$s_w \geq 0 \quad \forall w \in W \quad (7.27)$$

$$f_{ww'k} \geq 0 \quad \forall (w, w') \in W, k \in R \quad (7.28)$$

Constraints (7.18) to (7.21) are common with the Forbidden Sets formulation. Only a positive flow is allowed between tasks and this flow must not be greater than the resource consumption of the ending / starting task, as per (7.22). The input / output flows from a task must be both equal to the resource consumption: constraints (7.23) and (7.24) are the resource balance per activity. The total amount of a resource k on the flow is limited by (7.25). Finally, (7.26) to (7.28) are the domain constraints.

This formulation provides a poor linear relaxation, compared to discrete time formulations, although it can be preferable to them for instances involving large time scale. On top of this, it has been a widely studied formulation on its application for the TSP.

7.2.2.3 Event Based Formulations

Event Based Formulations for the RCSP were developed by Koné in 2009 [Koné, 2009], from a model introduced by Zapata, [Zapata JC, 2008]. These formulations define a series of events which correspond to the start or end of the different activities. They are based on the fact that

for the RCSP it always exists an optimal semi-active schedule in which the start time of an activity is either 0 or coincides with the completion time of another activity [Sprecher et al., 1995]. Therefore, at most $n + 1$ events have to be considered, and only n for the second Event Based Formulation I will discuss.

They have the advantage of not depending on the time horizon, making them especially relevant for long time projects. Koné proved that for some instances these formulations, and more precisely, the On/Off Event Based outperformed all the previous MILP formulations. On another set of instances these formulations even obtained better results than a specialized heuristic method.

Start/End Event Based Formulation (SEE) The Start/End Event Based Formulation (SEE) involves two types of binary variables, x_{we} and y_{we} , that are equal to 1 if task w starts (in the case of x_{we}) or ends (y_{we}) at event e and 0 otherwise. The time of each event is represented by the continuous variable t_e . As for the resources, the variables r_{ke}^* represent the amount of resource k needed immediately after the event e . The set of events is represented by E .

The SEE formulation can be written as follows:

Minimize:

$$z = t_n \quad (7.29)$$

Subject to:

$$t_0 = 0 \quad (7.30)$$

$$t_{e+1} - t_e \geq 0 \quad \forall e \in E \setminus \{n\} \quad (7.31)$$

$$\sum_e x_{we} = 1 \quad \forall w \in W \quad (7.32)$$

$$\sum_e y_{we} = 1 \quad \forall w \in W \quad (7.33)$$

$$\sum_f y_{wf} - \sum_e x_{we} \geq 1 \quad \forall w \in W \quad (7.34)$$

$$t_f - t_e - p_w x_{we} + p_w (1 - y_{wf}) \geq 0 \quad \forall w \in W, (e, f) \in E, e < f \quad (7.35)$$

$$\sum_{e'=e}^n y_{we'} + \sum_{e'=0}^{e-1} x_{w'e'} \leq 1 \quad \forall (w, w') \in A, \forall e \in E \quad (7.36)$$

$$r_{0k}^* = \sum_w b_{wk} x_{w0} \quad \forall k \in R \quad (7.37)$$

$$r_{ek}^* = r_{e-1k}^* + \sum_{w \in W} b_{wk} x_{we} - \sum_w b_{wk} y_{wk} \quad \forall e \geq 1, k \in R \quad (7.38)$$

$$r_{ek}^* \leq B_k \quad \forall e \in E, k \in R \quad (7.39)$$

$$x_{we} = \{0, 1\} \quad \forall w \in W, e \in E \quad (7.40)$$

$$y_{we} = \{0, 1\} \quad \forall w \in W, e \in E \quad (7.41)$$

$$t_e \geq 0 \quad \forall e \in E \quad (7.42)$$

The objective (7.29) is to minimize the time of the final event. The first event must start at the beginning of the project, (7.30), and events must be ordered in time, although two of them may have the same time, as per (7.31). Constraints (7.32) and (7.33) ensure that each activity has one and only one start/end event. Constraint (7.34) means that, for each activity, the end event must be after the start event. The duration of each activity must be at least its processing time by (7.35). The precedence constraints are (7.36).

As for the resources, the total available resources per type are limited by (7.39). The resources needed immediately after the first event are (7.37). From them onward, the resources needed after each event are calculated by the difference between the once consumed by the activities that end at event e and the ones beginning at that event (7.38).

To end with, (7.40) and (7.42) are the domain constraints.

This formulation involves $O(2n(n+1))$ binary variables, $(n+1)$ continuous variables, and $(n+1)(|R| + n^2/2 + |A|) + 3n$ non-redundant constraints. Compared with DT and DDT, this formulation involves a polynomial number of variables and constraints.

On/Off Event Based Formulation On/Off Event Based Formulation (OOE) uses only one set of binary variables: z_{we} . These variables are equal to 1 if activity w begins or is still active immediately after event e . Therefore, only n events are needed. As for the SEE based formulation, the continuous variable t_e is used for the time at which event e takes place.

In this formulation, there is no need for resource variables, as they can be controlled in an easier way. However, a new continuous variable c_{max} measures the project completion time.

Minimize:

$$z = c_{max} \quad (7.43)$$

Subject to:

$$t_0 = 0 \quad (7.44)$$

$$t_{e+1} - t_e \geq 0 \quad \forall e \in E \setminus \{n-1\} \quad (7.45)$$

$$c_{max} \geq t_e + (z_{we} - z_{we-1})p_w \quad \forall e \in E, w \in W \quad (7.46)$$

$$t_f - t_e \geq ((z_{we} - z_{we-1}) - (z_{wf} - z_{wf-1} - 1))p_w \quad \forall (e, f) \in E, f > e, w \in W \quad (7.47)$$

$$\sum_{e'=0}^{e-1} z_{we'} \leq e(1 - (z_{we} - z_{we-1})) \quad \forall e \in E - \{0\} \quad (7.48)$$

$$\sum_{e'=e}^{n-1} z_{we'} \leq (n - e)(1 + (z_{we} - z_{we-1})) \quad \forall e \in E - \{0\} \quad (7.49)$$

$$z_{we} + \sum_{e'=0}^e z_{w'e'} \leq 1 + (1 - z_{we})e \quad \forall e \in E, (w, w') \in A \quad (7.50)$$

$$\sum_{e=0}^{n-1} b_{wk} z_{we} \leq B_k \quad \forall e \in E, k \in R \quad (7.51)$$

$$z_{we} = \{0, 1\} \quad \forall w \in W, e \in E \quad (7.52)$$

$$t_e \geq 0 \quad \forall e \in E \quad (7.53)$$

Most of this formulation is based on the fact that $(z_{we} - z_{we-1}) = 0$ for most of the events, with the exception of the event after which an activity starts/ends, when $z_{we} - z_{we-1} = 1$ for the start and $z_{we} - z_{we-1} = -1$ for the end.

The objective function is represented by C_{max} , calculated in (7.46) as the sum of the last event in which a task starts and the task's completion time. The order of the events (7.45) and the starting of the project (7.44) are similar to the SEE formulation.

For each activity, (7.48) and (7.49) are non-preemption constraints: if activity w starts at event e it cannot be active before this event, and if it ends at event e it cannot be active afterwards. A minimum duration for the activity equal to its processing time is required by (7.47).

Constraints (7.50) are the precedence constraints and (7.51) the resource constraints. Variable domains are expressed by (7.52) and (7.53).

This formulation involves $O(n^2)$ binary variables (twice as few as SEE and the same number as FCT), $(n + 1)$ continuous variables, and $(n + 1)(3 + |A| + |R| + n^2) + n^2 n$ non-redundant constraints.

7.3 Model Formulation

From the different formulations referred to on the previous section, I will now use both of the Event Based Formulations. The Start/End Event (SEE) and ON/OFF Event (OOE) formulations will be addressed and improved in order to be able to use them for the final assembly line short term scheduling problem.

I will use four Sets, common to both SEE and OOE extended formulations, they are listed in Table 7.2. The parameters needed to define the model are listed in Table 7.3 and the common variables for both Event Based Formulations are listed in Table 7.4.

Table 7.2: Short Term Final Assembly Line Scheduling: Sets

W	All the Work Tasks. Index: w .
P	All the operator Profiles. Index: p .
A	All the Areas. Index: a
E	Set of events. The number of events depends on the formulation and it is related to the number of tasks to be scheduled. Index: e, e', e'', f .

Table 7.3: Short Term Final Assembly Line Scheduling: Parameters

Task Properties	D_w	Total duration (in working hours) of task $w \in W$, if assigned only to one operator; $\forall w \in W$
	Γ_{ow}	Reduction coefficient to obtain the work task's w 's duration when it is done by o operators; $\forall w \in W, MN_w \leq p \leq MX_w$
	P_{pw}	1 if task $w \in W$ can be done by operators with profile p and 0 otherwise; $\forall w \in W, o \in O$
	MX_w	Maximum number of operators that can work on task w ; $\forall w \in W$
	MN_w	Minimum number of operators that can work on task w ; $\forall w \in W$
	A_{aw}	1 If work task w is done on area a , 0 otherwise; $\forall a \in A, w \in W$
Precedence Graph	$PR_{ww'}$	1 if the precedence graph includes a precedence relationship between work tasks w, w' and 0 otherwise; $(w, w') \in W$
	$NP_{ww'}$	1 if the precedence graph includes a non-parallel constraint between work tasks, w, w' and 0 otherwise; $(w, w') \in W / w < w'$
	$MT_{ww'}$	1 if work task w' is to be begun Δ hours after w ends; $(w, w') \in W$. ($MT_{ww'} \leq PR_{ww'}$).
	Δ	Maximum time between the end of task w and the beginning of task w' when there exists a maximal time lag constraint between them.
Area Definition	C_a	Area Capacity (in terms of no. of operators) ; $\forall a \in A$
Cycle Time	CT	Station Cycle time
	M	Large enough number. $M = \max(CT, E)$

Table 7.4: Short Term Final Assembly Line Scheduling: Common Variables

Events	t_e	Time of event e
Operators	n_p	Total number of operators of profile p needed, $p \in P$
Start Time	t_w^i	Start time of task w . Used for maximal time lag constraints, and therefore defined only $\forall w \in W \sum_{w'} MTL_{ww'} + MTL_{w'w} > 0$

Table 7.5: SEE-M Variables

Start and End Event Variables	x_{weop}	1 if work task w starts at event e with o operators of profile p and 0 otherwise; $\forall w \in W, e < last(E), MN_w \leq o \leq MX_w, \forall p/P_{pw} = 1$
	y_{weop}	1 if work task w ends at event e with o operators of profile p and 0 otherwise; $\forall w \in W, e < first(E), MN_w \leq o \leq MX_w, \forall p/P_{pw} = 1$
Resources	r_{pe}^*	Number of operators of profile p required by the work tasks in progress immediately after event e , $\forall o \in O, e \in E$
Areas	s_{ae}^*	Number of operators on area a required by the tasks in progress immediately after event e , $\forall a \in A, e \in E$
NP work tasks	$\alpha_{ww'}$	1 if w ends before w' starts and 0 vice-versa. Defined $\forall w, w'/NP_{ww'} = 1$

7.3.1 Start End Event Based Multimode Formulation: SEE-M

The Start-End Event formulation proposed by Koné [Koné et al., 2011] deals with a single mode RCSP. For the final assembly line short term scheduling I needed to deal with a multi mode case, as each task may be performed by different operator profiles p and number of operators o . To do this, the variables x_{we} and y_{we} have been replaced by a sets of variables x_{weop} and y_{weop} , where $x_{weop} = 1$ ($y_{weop} = 1$) if task w starts (ends) at event e using o operators of profile p . Additional constraints were added to guarantee the same assignation of operator profiles and number throughout the task fulfillment.

I defined the non-negative variables r_{pe}^* to represent the amount of operators of profile p needed immediately after event e and non-negative variables s_{ae}^* to represent the number of operators working on area a immediately after event e .

Finally, on top of the precedence constraints from the original model, others dealing with non-parallel tasks and maximal time lags have been included.

In addition to the variables defined in table 7.4, some specific SEE-M variables must be used. They are listed in table 7.5.

For this formulation, the number of events is equal to the number of work tasks plus 1: $E = W + 1$.

The complete formulation is as follows:

Minimize:

$$z1 = \sum_p n_p \quad (7.54)$$

$$z2 = \sum_p n_p \times LT - \sum_w D_w \quad (7.55)$$

Subject to:

$$t_0 = 0 \quad (7.56)$$

$$t_e \leq CT \quad \forall e \neq \{0\} \quad (7.57)$$

$$t_{e+1} - t_e \geq 0 \quad \forall e \neq last(E) \quad (7.58)$$

$$\sum_{eop} ey_{weop} - \sum_{eop} ex_{weop} \geq 1 \quad \forall w \in W \quad (7.59)$$

$$\sum_{eop} x_{weop} = 1 \quad \forall w \in W \quad (7.60)$$

$$\sum_{eop} y_{weop} = 1 \quad \forall w \in W \quad (7.61)$$

$$t_f - t_e - \sum_o D_w \Gamma_{ow} x_{weop} + (D_w \Gamma_{ow})(1 - \sum_o y_{wfo}) \geq 0$$

$$\forall (f, e) \in E, f > e, w \in W, MN_w \leq o \leq MX_w \quad (7.62)$$

$$\sum_{ep} x_{weop} = \sum_{ep} y_{weop} \quad \forall w \in W, MN_w \leq o \leq MX_w \quad (7.63)$$

$$\sum_{eo} x_{weop} = \sum_{eo} y_{weop} \quad \forall w \in W, p \in P \quad (7.64)$$

$$\sum_{\substack{e'=0 \\ op}}^{e-1} x_{w'eop} + \sum_{\substack{e'=e \\ op}}^E y_{w'eop} \leq 1 \quad \forall e \in E, (w, w') \in W/PR_{ww'} = 1 \quad (7.65)$$

$$t_w^i \geq t_e - M(1 - \sum_{op} x_{weop}) \quad \forall w \in W / \sum_{w'} (MT_{ww'} + MT_{w'w}) > 0 \quad (7.66)$$

$$t_w^i \leq t_e + M(1 - \sum_{op} x_{weop}) \quad \forall w \in W / \sum_{w'} (MT_{ww'} + MT_{w'w}) > 0 \quad (7.67)$$

$$t_{w'}^i - t_w^i - \sum_{eop} \Gamma_{ow} D_w x_{weop} \leq \Delta \quad \forall (w, w') \in W / MT_{ww'} = 1 \quad (7.68)$$

$$\sum_{eop} ey_{weop} - \sum_{eop} ex_{w'eop} \leq M(1 - \alpha_{ww'}) \quad \forall (w, w') \in W/NP_{ww'} = 1 \quad (7.69)$$

$$\sum_{eop} ey_{w'eop} - \sum_{eop} ex_{weop} \leq M(\alpha_{ww'}) \quad \forall (w, w') \in W/NP_{ww'} = 1 \quad (7.70)$$

$$r_{p0}^* - \sum_{wo} ox_{w0op} = 0 \quad \forall p \in P \quad (7.71)$$

$$r_{pe}^* - r_{pe-1}^* + \sum_{\substack{w \\ P_{pw}=1}} (\sum_o oy_{weop} - \sum_o ox_{weop}) = 0 \quad \forall o \in O, e \in E - \{0\} \quad (7.72)$$

$$r_{pe}^* \leq n_p \quad \forall p \in P, e \in E \quad (7.73)$$

$$s_{a0}^* - \sum_{wop} ox_{w0op} A_{aw} = 0 \quad \forall a \in A \quad (7.74)$$

$$s_{ae}^* - s_{ae-1}^* + \sum_w (\sum_{op} oy_{weop} A_{aw} - \sum_{op} ox_{weop} A_{aw}) = 0 \quad \forall a \in A, e \in E - \{0\} \quad (7.75)$$

$$s_{ae}^* \leq C_a \quad \forall a \in A, e \in E \quad (7.76)$$

$$x_{weop} \in \{0, 1\} \quad \forall e \in E/\{0\}, w \in W, p \in P/P_{pw} = 1, MN_w \leq p \leq MX_w \quad (7.77)$$

$$y_{weop} \in \{0, 1\} \quad \forall e \in E/\{last(E)\}, w \in W, p \in P/P_{pw} = 1, MN_w \leq p \leq MX_w \quad (7.78)$$

$$r_{pe}^* \geq 0 \quad \forall e \in E, p \in P \quad (7.79)$$

$$s_{ae}^* \geq 0 \quad \forall e \in E, a \in A \quad (7.80)$$

$$t_e \geq 0 \quad \forall e \in E, (w, w') \in W / \alpha_{w,w'} \in \{0, 1\} \quad (7.81)$$

Objective Function The objective function is to minimize the production cost. This cost depends only on the labor costs. The labor costs are proportional to the maximum number of operators needed during the scheduling horizon, as resources allocated to a station will remain in it throughout the whole cycle time. Objective function (7.54) deals with the labor costs in terms of the total amount of operators. Objective function (7.55) minimizes the non-saturation of resources. Both of them would result on the same solution.

Order of the events Constraint (7.56) forces the first event to begin at $t=0$ and constraint (7.57) ensures that there is no delay in the station completion. The order of the events on time is imposed by constraint (7.58).

Start-End events for each task Constraint (7.59) states that the start event of a task must precede its end event. Constraints (7.60) and (7.61) limit to one the start and end event per work task. Constraints (7.59) can be omitted. However, they defines a smaller polytope and therefore a better linear relaxation.

Time per task Constraint (7.62) fixes the minimum time difference between the start and the end events to the duration of the task.

One mode per task A single mode for performing the task is imposed by constraints (7.63) and (7.64). Note that the possible modes are limited by the definition of x_{weop} and y_{weop} as they are only defined for $MN_w \leq o \leq MX_w$ and $\forall p / P_{pw} = 1$.

Temporal constraints As for the relationships between tasks: (7.65) is the multimode expression for the precedence constraints. It states that if w must precede w' then, if w finishes at event e , w' cannot start until event $e + 1$. Maximal time lags are imposed on constraints (7.66) to (7.68). Constraints (7.66) and (7.67) define the start time of a task. This constraints will only be calculated for the task involved on maximal time lag constraints, this is $\forall w \in W / \sum_{w'} (MT_{ww'} + MT_{w'w}) > 0$. Given (7.66) and (7.67) the tasks, (7.68) limits the time between the end of a task and the start of its successor. This time lag is defined as a constant parameter Δ but it can be easily replaced by a task dependent parameter: $\Delta_{ww'}$. In this constraints, M can be replaced by the station's cycle time, CT .

Constraints (7.69) and (7.70) define the non-parallel constraints. In this constraints, M can be replaced by the number of events.

Resource Needs The two sets of resources taken into account are the operators and the space on each of the station working areas. For operators, (7.71) is the number of operators needed per profile immediately after the first event. Constraint (7.72) deals with the number of operators per profile, p , for all the other events. Constraint (7.73) calculates the maximum need of operators per profile all over the events. Similarly, constraints (7.74) and (7.75) ensure that the maximum occupation in the station's working areas is not exceeded. Constraint (7.76) fixes the maximum capacity per area. As an alternative, this value can also be included as a domain restriction for s_{ae}^* , replacing (7.80).

Domain Restrictions are equations (7.77) to (7.81).

SEE-M Dimensions This formulation involves:

- $2EW \sum_w ((MX_w - MN_w) \sum_p P_{pw})$ start/end binary variables
- $|NP|$ extra binary variables for the Non-parallel relations
- $OE + AE + E + MT_w + O = E(O + A + 1) + MT_w + O$ continuous variables, corresponding to $r_{pe}^*, s_{ae}^*, t_e, t_w^i$ and n_p

The number of constraints is:

$$3W - 1 + E\left(\frac{(E-1)W}{2} \sum_w (MX_w - MN_w) + 2O + A + 2\right) + \sum_w (MX_w - MN_w) + \sum_{wp} P_{pw} + |PR| + |MT| + 2MT_w + 2|NP| - O.$$

Where: $|PR| = \sum_{ww'} PR_{ww'}$, $|NP| = \sum_{w,w'} NP_{w,w'}$,

$|MT| = \sum_{ww'} MT_{ww'}$ and MT_w is the number of work tasks for which $\sum_{w'} MT_{ww'} + MT_{w'w} > 0$.

For more detailed information about the number of constraints on SEE-M formulation, see Table 7.6.

At most $E = W + 1$. However, in some cases this number can be reduced. In that sense, it is important to note that the number of constraints is of the order of $(W + WE^2)$. This means that a reduction in the number of events has greater impact than lowering the number of work tasks.

In terms of W ($E = W + 1$), the number of constraints for SEE-M formulation is:

$$1 + O + A + W(5 + 2O + A) + W^2\left(\frac{\sum_w (MX_w - MN_w)}{2}\right) + W^3\left(\frac{\sum_w (MX_w - MN_w)}{2}\right) + \sum_w (MX_w - MN_w) + \sum_{ow} P_{pw} + |PR| + |MT| + 2MT_w + 2|NP|$$

Table 7.6: SEE-M Number of Constraints

Constraint Set	Number of Constraints
Order of the events	
Constraints 7.56:	1
Constraints 7.57:	$E - 1$
Constraints 7.58:	$E - 1$
Start-End events for each task	
Constraints 7.59:	W
Constraints 7.60 :	W
Constraints 7.61 :	W
Time per task	
Constraints 7.62:	$\frac{(E-1)(E)}{2} W \sum_w (MX_w - MN_w)$
One mode per task	
Constraints 7.63:	$\sum_w (MX_w - MN_w)$
Constraints 7.64 :	$\sum_{wp} P_{pw}$
Precedence constraints	
Constraints 7.65:	$ PR $
Maximal Time Lags	
Constraints 7.66:	MT_w
Constraints 7.67:	MT_w
Constraints 7.68 :	$ MT $
Non- Parallel Constraints	
Constraints 7.69 :	$ NP $
Constraints 7.69 :	$ NONP $
Scarce Resources	
Constraints 7.71:	O
Constraints 7.72:	$O(E - 1)$
Constraints 7.73:	$O(E - 1)$
Constraints 7.74:	A
Constraints 7.75 :	$A(E - 1)$

7.3.2 On-Off Event Based Multimode Formulation: OOE-M

Taking as a starting point the formulation presented by Koné [Koné et al., 2011], I introduced two new sub-index for the binary variables z_{we} , replacing them by z_{weop} , equal to 1 if work task w is active at event e with o operators of profile p . Additional constraints are added to guarantee the same number and operator profiles are used while the task is active. Also, together with the precedence constraints from the original model, others dealing with generalized temporal constraints have been added. In this formulation, there is no need for resource variables, as they can be controlled on an easier way.

In addition to the variables defined in Table 7.4, some OOE-M variables must be used. They are listed in Table 7.7.

The complete OOE-M Formulation is as follows:

Table 7.7: OOE-M Variables

Event Variables	z_{weop}	1 if work task w is active from event e to event $e + 1$ with p operators of profile o , 0 otherwise; $\forall e \in E, w \in W, o \in O/P_{pw} = 1, MN_w \leq p \leq MX_w$
Mode per Task	β_{wop}	1 if work task w is performed by p operators of profile o , 0 otherwise; $\forall w \in W, o \in O/P_{pw} = 1, MN_w \leq p \leq MX_w$

Minimize:

$$z1 = \sum_p n_p \quad (7.82)$$

$$z2 = \sum_p n_p \times LT - \sum_w D_w \quad (7.83)$$

Subject to:

$$t_0 = 0 \quad (7.84)$$

$$\sum_{wop} z_{w0op} \geq 1 \quad (7.85)$$

$$t_{e+1} - t_e \geq 0 \quad \forall e \neq \text{first}E \quad (7.86)$$

$$\sum_{eop} z_{weop} \geq 1 \quad \forall w \in W \quad (7.87)$$

$$\sum_p \beta_{wop} = 1 \quad \forall w \in W \quad (7.88)$$

$$MN_w \leq o \leq MX_w$$

$$z_{weop} \leq \beta_{wop} \quad \forall w \in W, p \in P, e \in E, MN_w \leq o \leq MX_w \quad (7.89)$$

$$\sum_{e' \leq e-1} \sum_{op} z_{we'op} - e(1 - \sum_{op} (z_{weop} - z_{we-1op})) \leq 0 \quad \forall w \in W, e \in E \quad (7.90)$$

$$\sum_{e'=e}^{E-1} \sum_{op} z_{we'op} - (E - e)(1 + (\sum_{op} (z_{weop} - z_{we-1op}))) \leq 0 \quad \forall w \in W, e \in E \quad (7.91)$$

$$t_f - t_e - \sum_{op} D_w \Gamma_{ow} (z_{weop} - z_{we-1op} - (z_{wfo} - z_{wf-1op})) \geq - \sum_{e'op} (D_w \Gamma_{ow} z_{we'op}) \quad (7.92)$$

$$\forall (f, e) \in E, f > e, w \in W$$

$$CT - t_e - \sum_{op} D_w \Gamma_{ow} (z_{weop} - z_{we-1op}) \geq 0 \quad \forall w \in W, e \in E \quad (7.93)$$

$$\sum_{op} z_{weop} + \sum_{e'=0}^e \sum_{op} z_{we'op} - (e - 1)(1 - \sum_{op} z_{weop}) \leq 1 \quad \forall e \in E, (w, w') \in W/PR_{ww'} = 1 \quad (7.94)$$

$$t_w^i \geq t_e - M(1 + z_{we-1op} - z_{weop}) \quad \forall e \in E, w \in W / \sum_{w'} (MT_{w,w'} + MT_{w',w}) \geq 1 \quad (7.95)$$

$$t_w^i \leq t_e + M(1 + z_{we-1op} - z_{weop}) \quad \forall e \in E, w \in W / \sum_{w'} (MT_{w,w'} + MT_{w',w}) \geq 1 \quad (7.96)$$

$$t_{w'}^i - (t_w^i + \sum_{op} \beta_{op} D_w \Gamma_{wp}) \leq \Delta \quad \forall (w, w') \in W / MT_{w,w'} = 1 \quad (7.97)$$

$$\sum_{op} z_{weop} + \sum_{op} z_{w'eop} \leq 1 + M(1 - NP_{ww'}) \quad \forall (w, w') \in W / NONP_{w, w'} = 1 \quad (7.98)$$

$$\sum_{wo} oz_{weop} \leq n_p \quad \forall p \in P, e \in E \quad (7.99)$$

$$\sum_{wop} oz_{weop} A_{aw} \leq C_a \quad \forall a \in A, e \in E \quad (7.100)$$

$$z_{ewop} \in \{0, 1\} \quad \forall e \in E, w \in W, p \in P, MN_w \leq o \leq MX_w \quad (7.101)$$

$$z_{w-1op} = 0 \quad \forall w \in W, p \in P, MN_w \leq o \leq MX_w \quad (7.102)$$

$$\beta_{wop} \in \{0, 1\} \quad \forall w \in W, p \in P, MN_w \leq o \leq MX_w \quad (7.103)$$

$$t_e \geq 0 \quad \forall e \in E \quad (7.104)$$

$$t_w^i \geq 0 \quad \forall w \quad (7.105)$$

Objective Function The objective function is to minimize the total production cost. The two both possible formulations proposed for the SEE-M are valid for the OOE-M: (7.82) and (7.83).

Order of the events The first event on the station starts at $t = 0$ per constraint (7.84) and at least one task must be active after this event as per, (7.85). Constraint (7.86) refers to the order of the events, allowing two of them to occur at the same time.

At least one active event per task Each task must be active at least after one of the events per (7.87). This ensures the scheduling of all the tasks.

One mode per task Variables β_{wop} are used to select the mode in which each task will be performed. Only one of the variables β_{wop} can be set to 1 per constraint (7.88) and the tasks can only be performed on the selected mode, as per (7.89).

From now on, I will use *start event* of a task w to refer to the first event e after which w is active. Similarly, the *end event* of task w will be used to refer to the last event after which w is active. Moreover, most of the following constraints are based on the three values than can take the difference between $z_{weop} - z_{we+1on}$:

- $z_{weop} - z_{we+1op} = -1$. When $e + 1$ is the first event after which w is active, so $z_{weop} = 0$ and $z_{we+1op} = 1$.
- $z_{weop} - z_{we+1op} = 1$. When e is the last event after which w is active, so $z_{weop} = 1$ and $z_{we+1op} = 0$.
- $z_{weop} - z_{we+1op} = 0$. Otherwise.

Continuous processing of each work task Constraint (7.90) means that if task w begins after event e , then it can not be processed before $e - 1$. Constraint (7.91) states that if task w ends at event e then w is no longer active $\forall e' \geq e + 1$.

Time per task The time difference between w 's start event and its end event must be at least the work task's processing time, as per (7.92).

Station Cycle Time The time when a work task ends can be calculated by adding the work task's processing time to the time at which its start event takes place. Constraint (7.93) means that, in order to cope with the cycle time restriction, all the work tasks' completion times must be smaller than the station's cycle time.

Temporal Constraints If w must precede w' , then it must start at an event after which w is no more active as per (7.94).

Maximal time lags are imposed by constraints (7.95) to (7.97). Constraints (7.95) and (7.96) define the start time of a task. This constraints will only be calculated for the tasks involved on maximal time lag constraints. Given (7.95) and (7.96), (7.97) limits the time between the end of a task and its successor's start time. This time lag is defined as a unique parameter Δ but if needed it can be easily transformed on a parameter dependent on the pair of tasks, $\Delta_{ww'}$.

Non-parallel constraints are (7.98), as two non-parallel tasks cannot be active at the same time.

Resources Resource constraints are easier than for the SEE-M formulation. In this case, only one set of constraints is defined per scarce resource: (7.99) for the quantity of operators per type and (7.100) for the amount of operators per area.

OOE-M Dimensions I will use E' for the number of events used in OOE-M formulation, to distinguish it from the number of events needed in the SEE-M.

This formulation involves:

- $E'W \sum_w ((MX_w - MN_w) \sum_p P_{pw})$ event binary variables
- $W \sum_w ((MX_w - MN_w) \sum_p P_{pw})$ extra binary variables for the mode selection
- $E' + MT_w + O$ continuous variables, corresponding to t_e, t_w^i and n_p

The number of constraints is:

$$1 + E' + 2W + WE'(3 + \frac{(E'-1)}{2} \sum_w (MX_w - MN_w) \sum_{pw} P_{pw}) + |PR| + |MT| + 2MT_w + |NP| + OE' + AE'.$$

Where: $|PR| = \sum_{ww'} PR_{ww'}$, $|NP| = \sum_{w,w'} NP_{w,w'}$,

$|MT| = \sum_{ww'} MT_{ww'}$ and MT_w is the number of work tasks for which

Table 7.8: OOE-M Number of Constraints

Constraint Set	Number of Constraints
Order of the events	
Constraints 7.84:	1
Constraints 7.85 :	1
Constraints 7.86:	$E' - 1$
Constraints 7.87:	W
Constraints 7.93 :	WE'
Tasks' non-preemption	
Constraints 7.90 :	WE'
Constraints 7.91 :	WE'
Time per task	
Constraints 7.92:	$\frac{(E'-1)(E')}{2}W$
One mode per task	
Constraints 7.88:	W
Constraints 7.89 :	$E'W \sum_w ((MX_w - MN_w) \sum_p P_{pw})$
Precedence constraints	
Constraints 7.94 :	$ PR $
Maximal Time Lags	
Constraints 7.95:	MT_w
Constraints 7.96:	MT_w
Constraints 7.97 :	$ MT $
Non- Parallel Constraints	
Constraints 7.98 :	$ NP $
Scarce Resources	
Constraints 7.99:	OE'
Constraints 7.100:	AE'

$$\sum_{w'} MT_{ww'} + MT_{w'w} > 0.$$

For more detailed information about the number of constraints on OOE-M formulation, see Table 7.8.

At most $E' = W$. However, in some cases this number can be reduced. In that sense, it is important to note that the number of constraints is of the order of $(W + WE'^2)$. This means that a reduction in the number of events has greater impact than lowering the number of work tasks.

In terms of W , the number of constraints for this formulation is:

$$W(3 + O + A) + W^2 \left[3 - \frac{\sum_w (MX_w - MN_w) \sum_p P_{pw}}{2} \right] + W^3 \left[\frac{\sum_w (MX_w - MN_w) \sum_p P_{pw}}{2} \right] \\ |PR| + |MT| + 2MT_w + |NP| + 1$$

7.3.3 Comparison between SEE-M and OOE-M Event Based Multimode Formulations

The OOE-M formulation involves less binary variables than the SEE-M:

Table 7.9: Instance Characteristics

Set	No. Tasks	Preced.	$\sum$ MTL	$\sum$ NONP	Op. Profiles	Areas	No. Modes
Set1-8	8	6	1	1	2	2	12
Set2-8	8	8	1	1	2	2	16
Set3-8	8	7	1	1	2	2	17
Set4-8	8	7	1	1	2	2	16

Table 7.10: Extended Instance Characteristics

Set	No. Tasks	Preced.	$\sum$ MTL	$\sum$ NONP	Op. Profiles	Areas	No. Modes
Set3-9	9	8	1	1	2	2	18
Set3-10	10	9	1	1	2	2	18
Set3-11	11	10	1	1	2	2	18
Set4-9	9	8	1	1	2	2	16
Set4-10	10	9	1	1	2	2	16
Set4-11	11	10	1	1	2	2	16

$((W + 1)(W \sum_w ((MX_w - MN_w) \sum_p P_{pw}))$ less for the event variables and $|NP|$ less for the non parallel constraints.

The number of continuous variables is also fewer on for the OOE-M, with $(O + A)(W + 1)$ constraints less.

As for the number of constraints, for precedence and maximal time lag constraints, both models are similar. The SEE-M has twice as constraints as the OOE-M for defining the non-parallel constraints. On all, it is not possible to establish a general dominance rule.

7.4 Experimentation

The computational results were obtained using CPLEX12.4 solver. The tests were carried out on an Intel-Core i7-2630QM processor with 2GHz and 4 GB RAM, running Windows 7.

The AIMMS modeling environment was used for the implementation of the MILP formulation [Roelofs and Bisschop, 2011]. As well as this, an interface for input data via Excel was developed. Although not strictly necessary for the initial experimentation, it is an enabler for future real-world instance solution.

RCSP formulations and methods are usually benchmarked using PSPLIB instances. However, this library [Kolisch and Sprecher, 1997] does not have any instances valid for the structure of the current problem. In consequence, four new sets of 8 task instances were used for the experimentation. Table 7.9 summarizes the main instance characteristics. Sets 3 and 4 were extended in order to create instances of up to 11 tasks. Their characteristics are listed in Table 7.10.

In all, 75 different combinations of data sets, number of tasks, cycle time and number of events were tested for each formulation. The most important conclusions from the experimentation will

be explained in the next subsections. Nevertheless, all the computational results are listed at the end of this section (Subsection 7.4.4).

7.4.1 SEE-M Results

All instances were solved up to optimality, taking times from seconds to fifteen minutes. For each set and cycle time, different number of events were tested. Starting from the theoretical minimum number of events, they were reduced until solutions where no longer optimal. As it was expected, following the conclusions from Section 7.3, the solution time decreased exponentially with the number of events, even when solving the same set of instances. The first Set (Set1-8), solved for a CT=11,5 days took from 2 to 281 seconds, depending on the number of events. The harder instance to solve was Set3-11, that took up to 4133 seconds for a CT=17 days and 11 events.

Figure 7.3 shows the evolution of the SEE-M solution times for a same instance and cycle time whenever the number of events changed. On this figure the series data include information on the data set, the number of tasks and the cycle time: Set1-8-11.5 stands for the solution of data set 1, with 8 tasks and a CT=11.5 days.

The event reduction not only lowers the number of variables but also reduces the integrality gap, as it defines a tighter polyhedron. In some cases, the integrality gap is reduced by improving the First Lower Bound (FLB) but also the First Integer Solutions (FIS). However, the improvement on the First Integer Solution does not always happen. For example, Set2-8 with CT=33, if solved with 7 events has a First Lower Bound FLB=1,84 and First Integer Solutions FIS=7. For the same set, defining 10 events, the first solutions are FLB=0,29 and FIS=10. In fact, with 10 events, the number of explored nodes is 136 times bigger than with 7 events (405935 vs 2981). The relationship between the number of events and the FLB is plotted in Figure 7.4, using a the same set nomenclature as Figure 7.3.

Table 7.11 includes the main information to measure the performance during the scheduling of the 8 tasks sets. Columns 1 to 3 are related to the input data: the first column is used to identify the set of instances, where **Set1-8** stands for the first data set with 8 tasks. The second column shows the **cycle time**. Finally, the third column is the **number of events** used in that instance. Columns 4 to 8 refer to the results. The **nodes** are the number of nodes explored on the Branch & Bound until the optimal solution. The **first lower bound (FLB)** and **first integer solution (FIS)** include the value of this first solutions. As for the **Solution t**, it is the time to provide the optimal solution, in seconds. The last column is the **optimal number of resources**.

As for the evolution of the solution time throughout different cycle times, on average the solution time also grew as the objective cycle Time got closer to the critical path's lead time. In Table 7.12, it can be seen the solution time for Set2-8 instance and different cycle times.

Finally, focusing on the influence of the number of tasks, most of the instances required more solution time with the same number of events when new tasks are added. Withal, some

Figure 7.3: SEE-M Solution Time vs Number of Events

were solved faster with more tasks. This shows that in some cases the structure of the problem is more important than the number of tasks itself. It can be also stated that the hardening of the instances as new tasks are added is wider on the cases where more events are used. The relationship between the solution time and the number of tasks has been plotted in Figure 7.5. Here, each series of data represents the solution of a same set with a fixed number of events adding different number of tasks: Set3-8E states for the third Set solved with 8 Events and 8 to 11 tasks.

Figure 7.4: SEE-M First Lower Bound vs Number of Events

Table 7.11: Number of Events Impact in SEE-M Results

Instance	CT	Events	Nodes	FLB	FIS	Solution t (sec)	Optimal Sol
Set1-8	11,5	7	1546	2,3	10	1,97	8
Set1-8	11,5	9	11203	1,92	9	21,09	8
Set1-8	11,5	11	105195	1,63	11	281	8
Set1-8	15,5	7	3777	2,3	10	7	6
Set1-8	15,5	8	13203	1,75	9	17,32	6
Set1-8	15,5	10	219403	1,12	9	282,97	6
Set2-8	31,5	7	7069	1,85	9	10,2	7
Set2-8	31,5	8	31116	1,194	9	39,76	7
Set2-8	31,5	9	119162	0,64	8	176,98	7
Set2-8	31,5	10	511955	0,29	10	1215,95	7
Set2-8	33	7	2981	1,84	7	6,65	6
Set2-8	33	8	25778	1,194	8	46,49	6
Set2-8	33	9	45205	0,64	9	116,81	6
Set2-8	33	10	405935	0,29	10	1007,87	6
Set2-8	34,75	8	1912	1,19	10	3,39	5
Set2-8	34,75	9	6926	0,64	11	19,66	5
Set2-8	34,75	10	10619	0,296	9	44,69	5
Set2-8	34,75	11	28112	0,07	8	142,52	5
Set2-8	34,75	13	75825	0,01	10	663,27	5
Set3-8	14	6	472	2,8	8	0,61	6
Set3-8	14	7	4631	1,7	8	6,35	6
Set3-8	14	8	23407	1,13	7	34,4	6
Set3-8	14	9	94129	0,69	7	121,98	6
Set3-8	14	10	506132	0,36	8	776,76	6
Set4-8	13	6	112	3,05	7	0,3	7
Set4-8	13	7	1957	2,14	8	2,2	7
Set4-8	13	8	3341	1,43	8	6,85	7
Set4-8	13	9	29076	0,92	9	36,58	7
Set4-8	13	10	127109	0,55	9	193,25	7
Set4-8	13	11	422579	0,26	9	905,13	7

Table 7.12: Sample SEE-M Solving Time for Different Cycle Times

Instance	CT=31.5	CT=33	CT=34.75	CT=41
Set2-8	10.2s	6.65s	1.79s	0.83s

Figure 7.5: SEE-M Solution Time vs Number of Tasks

7.4.2 OOE-M Results

The same instances were used for the computational study of OOE-M formulation. All instances were solved up to optimality. In this case, they took times from 0,1 seconds to eight minutes. As happened with the SEE-M formulation, the solution time decreased exponentially with the number of events, even when solving the same set of instances. For example, Set3 with 8 tasks (Set3-8) and CT=14 days, was solved in times from 0.2 to 181 seconds. The harder instance to solve was the eleven tasks Set3 (Set3-11), which took 452 seconds for CT=17 and 11 events. This was also the harder instance for the SEE-M formulation.

Figure 7.6 shows the evolution of the OOE-M solution times for a same instance and cycle time whenever the number of events changed. On this figure, the series data include information on the data set, the number of tasks and the cycle time: Set1-8-11.5 stands for the solution of data set 1, with 8 tasks and a CT=11.5 days.

As in the SEE-M formulation, the first lower bound increased when lowering the number of events at the same time that the number of nodes to be visited before the optimal solution became lower. I will use as an example Set3, when tested with CT=14 and 5 to 10 events. The FLB varied from 3,8 to 1,47 and the number of visited nodes grew from 72 to 261475. The relationship between the number of events and the FLB is plotted in Figure 7.7, where the series of data are numbered as in Figure 7.6

Table 7.13 includes all the data about nodes, First Lower Bound (FLB), First Integer Solution (FIS), solution time and optimal solution for the four sets with 8 tasks when solved for different cycle times and number of events.

As for the evolution of the solution time throughout different cycle times, on average the solution time also grew as the objective cycle time got closer to the critical path's lead time. Table 7.14, shows the solution time of Set2-8 instance for different cycle times.

To end with, most of the instances required more solution time with the same number of events when new tasks are added. Withal, some were also solved faster with more tasks. As well as this, the hardening of the instances as new tasks are added is wider on the cases were more events are used. The relationship between the solution time and the number of tasks has been plotted in Figure 7.8. As it happened in SEE-M's Figure 7.5, each series of data represents the solution of a same set with a fixed number of events adding different number of tasks: Set3-8E states for the third set solved with 8 events and 8 to 11 tasks.

Figure 7.6: OOE-M Solution Time Vs Number of Events

Figure 7.7: OOE-M First Lower Bound vs Number of Events

Table 7.13: Number of Events Impact in OOE-M Results

Instance	CT	Events	Nodes	FLB	FIS	Solution t (sec)	Optimal Sol
Set1-8	11,5	7	478	2,4	10	0,67	8
Set1-8	11,5	9	1918	2,29	10	1,93	8
Set1-8	11,5	11	10688	2,22	10	12,68	8
Set1-8	15,5	7	857	2,2	10	0,8	6
Set1-8	15,5	8	1385	1,92	6	1,33	6
Set1-8	15,5	10	11416	1,525	10	10,72	6
Set2-8	31,5	7	3561	3,6	8	4,66	7
Set2-8	31,5	8	10998	3,5	7	10,58	7
Set2-8	31,5	9	18506	3,43	7	20,05	7
Set2-8	31,5	10	48674	3,38	7	61,11	7
Set2-8	33	7	678	3,6	6	0,83	6
Set2-8	33	8	2852	3,5	7	2,65	6
Set2-8	33	9	10683	3,43	7	10,3	6
Set2-8	33	10	7793	3,34	6	9,63	6
Set2-8	34,75	7	141	3,6	7	0,47	5
Set2-8	34,75	8	93	3,5	7	0,58	5
Set2-8	34,75	9	630	3,43	6	1,45	5
Set2-8	34,75	10	276	3,34	6	1,11	5
Set2-8	34,75	11	177	3,33	7	1,14	5
Set2-8	34,75	13	150	3,3	5	1,45	5
Set3-8	14	5	72	3,8	7	0,22	6
Set3-8	14	6	837	2,58	7	0,87	6
Set3-8	14	7	2207	2,14	7	2,14	6
Set3-8	14	8	8593	1,85	7	8,24	6
Set3-8	14	9	21865	1,64	7	19,31	6
Set3-8	14	10	261475	1,47	8	181,07	6
Set4-8	13	5	0	4,74	7	0,11	7
Set4-8	13	6	408	2,5	9	0,65	7
Set4-8	13	7	1819	2,14	8	2,06	7
Set4-8	13	8	3460	1,88	7	3,82	7
Set4-8	13	9	16935	1,67	9	17,18	7
Set4-8	13	10	53020	1,5	8	45,66	7
Set4-8	13	11	25773	1,36	8	29,28	7

Table 7.14: Sample OOE-M Solving Time for Different Cycle Times

Instance	CT=31.5	CT=33	CT=34.75	CT=41
Set2-8	4.66s	0.83s	0.47s	0.2s

Figure 7.8: OOE-M Solution Time vs Number of Tasks

7.4.3 SEE-M and OOE-M Comparative Study

By comparing sections 7.4.1 and 7.4.2, it is clear that both models have similar behavior as far as the impact of variations on the number of events, number of tasks and cycle time on the solution time.

The results in terms of solution time, number of nodes and first lower bound have been better for all the instances with the OOE-M formulation than with the SEE-M formulation. Figure 7.9 shows the histogram for the division of the time spent for a solution with the OOE-M formulation between the time spent by the SEE-M formulation. The only two cases where the solution time is longer for the OOE-M formulation are instances with solution times within the range of 0,5 seconds, where the absolute difference is not relevant.

Figure 7.9: OOE-M Solution Time / SEE-M Solution Time

Table 7.15 compares all the performance measures for several cases on the SEE-M and OOE-M formulations. There, it is easy to see that the difference between both formulations grows with the number of events. Therefore, as the complexity of the instances grows the use of the OOE-M formulations becomes more and more suitable. It is also important to remember that, although the comparison has been made between instances with the same number of events, the OOE-M formulation is always capable of calculating a solution using one event less than the SEE-M formulation. Hence, the performance difference between both formulations is even bigger.

This comparative results are coherent with the results from Koné [Koné et al., 2011] for the mono-mode case with only precedence constraints, who concluded that the OOE outperformed the SEE formulation for all the instance sets. As stated by [Tsai, 2006], a good formulation must have two characteristics: its tightness and its compactness. The tightness refers to the quality of its approximation to the convex hull of integer feasible solutions and the compactness is a measure of the number of variables and constraints that are used to formulate a given problem. The OOE-M is better than the SEE-M formulation in both aspects.

Table 7.15: SEE-M and OOE-M Performance Comparison

Set-Tasks-LT-Ev	FLB		FIS		Nodes		Sol t.	
	SEE-M	OOE-M	SEE-M	OOE-M	SEE-M	OOE-M	SEE-M	OOE-M
Set1-8-11,5-7	2,3	2,4	10	10	1546	478	1,97	0,67
Set1-8-11,5-9	1,92	2,29	9	10	11203	1918	21,09	1,93
Set1-8-11,5-11	1,63	2,22	11	10	105195	10688	281	12,68
Set1-8-15,5-7	2,3	2,2	10	10	3777	857	7	0,8
Set1-8-15,5-8	1,75	1,92	9	6	13203	1385	17,32	1,33
Set1-8-15,5-10	1,12	1,525	9	10	219403	11416	282,97	10,72
Set2-8-31,5-7	1,85	3,6	9	8	7069	3561	10,2	4,66
Set2-8-31,5-8	1,194	3,5	9	7	31116	10998	39,76	10,58
Set2-8-31,5-9	0,64	3,43	8	7	119162	18506	176,98	20,05
Set2-8-31,5-10	0,29	3,38	10	7	511955	48674	1215,95	61,11
Set2-8-33-7	1,84	3,6	7	6	2981	678	6,65	0,83
Set2-8-33-8	1,194	3,5	8	7	25778	2852	46,49	2,65
Set2-8-33-9	0,64	3,43	9	7	45205	10683	116,81	10,3
Set2-8-33-10	0,29	3,34	10	6	405935	7793	1007,87	9,63
Set2-8-34,75-8	1,19	3,5	10	7	1912	93	3,39	0,58
Set2-8-34,75-9	0,64	3,43	11	6	6926	630	19,66	1,45
Set2-8-34,75-11	0,07	3,33	8	7	28112	177	142,52	1,14
Set2-8-34,75-13	0,01	3,3	10	5	75825	150	663,27	1,45
Set3-8-14-6	2,8	2,58	8	7	472	837	0,61	0,87
Set3-8-14-7	1,7	2,14	8	7	4631	2207	6,35	2,14
Set3-8-14-9	0,69	1,64	7	7	94129	21865	121,98	19,31
Set3-8-14-10	0,36	1,47	8	8	506132	261475	776,76	181,07
Set4-8-13-6	3,05	2,5	7	9	112	408	0,3	0,65
Set4-8-13-8	1,43	1,88	8	7	3341	3460	6,85	3,82
Set4-8-13-10	0,55	1,5	9	8	127109	53020	193,25	45,66
Set4-8-13-11	0,26	1,36	9	8	422579	25773	905,13	29,28

7.4.4 Experimentation Results Tables

Results with the SEE-M model are listed in Tables 7.16 to 7.18. Moreover, results with the OOE-M model are listed in Tables 7.19 to 7.21.

The information included for each experiment is:

- Instance: Identifies the set of data (Set 1 to Set 4) and the number of tasks.
- CT: Station cycle time.
- Events: Number of events defined.
- Nodes: Number of explored nodes until the optimal solution was found.
- FLB: First lower bound.
- FIS: First integer solution.
- Solution t (secs): Time spent until the optimal solution was found, in seconds.
- Optimal sol: Number of operators used in the optimal solution.

Table 7.16: SEE-M Computational Results for Sets 1 & 2

Instance	CT	Events	Nodes	FLB	FIS	Solution t (secs)	Optimal Sol
Set1-8	11,5	7	1546	2,3	10	1,97	8
Set1-8	11,5	9	11203	1,92	9	21,09	8
Set1-8	11,5	11	105195	1,63	11	281	8
Set1-8	12	8	13245	2,17	11	25,49	8
Set1-8	12	10	86618	1,12	9	149,45	8
Set1-8	13,5	8	6061	2,28	10	10,2	8
Set1-8	15,5	7	3777	2,3	10	7	6
Set1-8	15,5	8	13203	1,75	9	17,32	6
Set1-8	15,5	10	219403	1,12	9	282,97	6
Set1-8	16	10	204733	1,12	9	273,67	6
Set2-8	31,5	7	7069	1,85	9	10,2	7
Set2-8	31,5	8	31116	1,194	9	39,76	7
Set2-8	31,5	9	119162	0,64	8	176,98	7
Set2-8	31,5	10	511955	0,29	10	1215,95	7
Set2-8	33	7	2981	1,84	7	6,65	6
Set2-8	33	8	25778	1,194	8	46,49	6
Set2-8	33	9	45205	0,64	9	116,81	6
Set2-8	33	10	405935	0,29	10	1007,87	6
Set2-8	34,75	7	1180	1,84	7	1,79	5
Set2-8	34,75	8	1912	1,19	10	3,39	5
Set2-8	34,75	9	6926	0,64	11	19,66	5
Set2-8	34,75	10	10619	0,296	9	44,69	5
Set2-8	34,75	11	28112	0,07	8	142,52	5
Set2-8	34,75	13	75825	0	10	663,27	5
Set2-8	41	7	152	1,84	7	0,83	5
Set2-8	55	7	2804	0,64	5	8,22	5
Set2-8	85	7	1277	0,64	8	4,29	5

Table 7.17: SEE-M Computational Results for Set 3

Instance	CT	Events	Nodes	FLB	FIS	Solution t (secs)	Optimal Sol
Set3-8	13	9	169911	0,68	9	245,64	7
Set3-8	14	6	224	2,8	8	0,48	6
Set3-8	14	6	472	2,8	8	0,61	6
Set3-8	14	7	4631	1,7	8	6,35	6
Set3-8	14	8	23407	1,13	7	34,4	6
Set3-8	14	9	94129	0,69	7	121,98	6
Set3-8	14	10	506132	0,36	8	776,76	6
Set3-8	14,5	8	4785	1,13	7	12,31	5
Set3-8	15	8	2533	1,13	8	5,37	5
Set3-8	33	8	2203	1,13	6	6,46	5
Set3-9	17	8	1799	1,18	7	4,87	5
Set3-9	17	9	5214	0,73	7	27,5	5
Set3-9	17	10	20731	0,38	7	100,5	5
Set3-9	17	11	24707	0,08	9	138,72	5
Set3-10	17	8	1781	1,64	11	4,56	5
Set3-10	17	9	14574	1,07	11	46,11	5
Set3-10	17	10	17275	0,67	8	69,78	5
Set3-10	17	11	68836	0,36	7	270,86	5
Set3-11	15	9	116110	1,31	13	314,08	8
Set3-11	16	8	15309	1,93	10	29,06	7
Set3-11	16,5	9	172701	1,31	9	396,6	7
Set3-11	16,8	9	51814	1,31	13	112,46	6
Set3-11	17	8	5662	1,93	9	16,21	6
Set3-11	17	9	29692	1,31	9	66,94	6
Set3-11	17	10	183981	0,86	9	586,13	6
Set3-11	17	11	1233159	0,54	12	4133	6
Set3-11	17,9	8	4856	1,93	12	11,98	6
Set3-11	18	9	3070	1,32	9	21,12	5
Set3-11	24	9	1324	1,31	9	7,19	5
Set3-11	24	12	1324	0,33	6	116,67	5

Table 7.18: SEE-M Computational Results for Set 4

Instance	CT	Events	Nodes	FLB	FIS	Solution t (secs)	Optimal Sol
Set4-8	12	9	22454	0,92	9	30,5	8
Set4-8	13	6	112	3,05	7	0,3	7
Set4-8	13	7	1957	2,14	8	2,2	7
Set4-8	13	8	3341	1,43	8	6,85	7
Set4-8	13	9	29076	0,92	9	36,58	7
Set4-8	13	10	127109	0,55	9	193,25	7
Set4-8	13	11	422579	0,26	9	905,13	7
Set4-8	13,8	9	21919	0,92	8	49,12	6
Set4-8	15	10	57007	0,55	8	94,22	6
Set4-9	13	8	5250	1,57	8	9,83	7
Set4-9	13	9	20828	1,04	8	38,02	7
Set4-9	13	10	162585	0,65	8	285,26	7
Set4-10	13	8	2940	1,87	9	7,38	8
Set4-10	13	9	75062	1,29	10	107,41	8
Set4-10	13	10	151881	0,86	10	269,79	8
Set4-11	13	8	16314	2,02	8	28,2	8
Set4-11	13	9	108599	1,4	9	149,5	8
Set4-11	13	10	202190	0,94	10	473,54	8

Table 7.19: OOE-M Computational Results for Sets 1 & 2

Instance	CT	Events	Nodes	FLB	FIS	Solution t (secs)	Optimal Sol
Set1-8	11,5	7	478	2,4	10	0,67	8
Set1-8	11,5	9	1918	2,29	10	1,93	8
Set1-8	11,5	11	10688	2,22	10	12,68	8
Set1-8	12	8	1885	1,92	8	1,9	8
Set1-8	12	10	5514	1,525	8	6,27	8
Set1-8	13,5	8	1929	1,92	8	1,59	8
Set1-8	15,5	7	857	2,2	10	0,8	6
Set1-8	15,5	8	1385	1,92	6	1,33	6
Set1-8	15,5	10	11416	1,525	10	10,72	6
Set1-8	16	10	9725	1,525	10	9,75	6
Set2-8	31,5	7	3561	3,6	8	4,66	7
Set2-8	31,5	8	10998	3,5	7	10,58	7
Set2-8	31,5	9	18506	3,43	7	20,05	7
Set2-8	31,5	10	48674	3,38	7	61,11	7
Set2-8	33	7	678	3,6	6	0,83	6
Set2-8	33	8	2852	3,5	7	2,65	6
Set2-8	33	9	10683	3,43	7	10,3	6
Set2-8	33	10	7793	3,34	6	9,63	6
Set2-8	34,75	7	141	3,6	7	0,47	5
Set2-8	34,75	8	93	3,5	7	0,58	5
Set2-8	34,75	9	630	3,43	6	1,45	5
Set2-8	34,75	10	276	3,34	6	1,11	5
Set2-8	34,75	11	177	3,33	7	1,14	5
Set2-8	34,75	13	150	3,3	5	1,45	5
Set2-8	41	7	0	3,6	6	0,2	5
Set2-8	55	7	0	3,6	5	0,16	5
Set2-8	85	7	0	3,6	5	0,14	5

Table 7.20: OOE-M Computational Results for Set 3

Instance	CT	Events	Nodes	FLB	FIS	Solution t (secs)	Optimal Sol
Set3-8	13	9	32799	1,63	8	31,08	7
Set3-8	14	5	72	3,8	7	0,22	6
Set3-8	14	6	837	2,58	7	0,87	6
Set3-8	14	6	837	2,58	7	0,87	6
Set3-8	14	7	2207	2,14	7	2,14	6
Set3-8	14	8	8593	1,85	7	8,24	6
Set3-8	14	9	21865	1,64	7	19,31	6
Set3-8	14	10	261475	1,47	8	181,07	6
Set3-8	14,5	8	583	1,86	6	1,58	5
Set3-8	15	8	193	1,86	6	0,98	5
Set3-8	33	8	0	1,86	5	0,84	5
Set3-9	17	7	40	2,3	7	0,39	5
Set3-9	17	8	110	2	6	0,83	5
Set3-9	17	9	0	1,78	5	1,2	5
Set3-9	17	10	154	1,6	6	1,67	5
Set3-9	17	11	1128	1,45	11	3,95	5
Set3-10	17	8	3087	2,25	7	3,93	5
Set3-10	17	9	3852	2	8	7,86	5
Set3-10	17	10	520	1,8	9	2,96	5
Set3-10	17	11	977	1,63	7	3,4	5
Set3-11	15	9	52967	2,22	12	72,62	8
Set3-11	16	8	9072	2,5	9	14,02	7
Set3-11	16,5	9	91839	2,22	10	104,27	7
Set3-11	16,8	9	22988	2,22	10	27,67	6
Set3-11	17	7	793	2,89	7	1,45	6
Set3-11	17	8	4081	2,5	9	5,16	6
Set3-11	17	9	20542	2,22	8	22,99	6
Set3-11	17	10	82736	2	8	82,21	6
Set3-11	17	11	467471	1,82	7	452,53	6

Table 7.21: OOE-M Computational Results for Set 4

Instance	CT	Events	Nodes	FLB	FIS	Solution t (secs)	Optimal Sol
Set4-8	13	5	0	4,74	7	0,11	7
Set4-8	13	6	408	2,5	9	0,65	7
Set4-8	13	7	1819	2,14	8	2,06	7
Set4-8	13	8	3460	1,88	7	3,82	7
Set4-8	13	9	16935	1,67	9	17,18	7
Set4-8	13	10	53020	1,5	8	45,66	7
Set4-8	13	11	25773	1,36	8	29,28	7
Set4-8	13,8	9	5386	1,67	7	6,22	6
Set4-8	15	10	8232	1,5	6	9,94	6
Set4-9	13	8	7490	2	8	7,83	7
Set4-9	13	9	9479	1,78	8	11,18	7
Set4-9	13	10	46245	1,6	8	47,58	7
Set4-10	13	8	20033	2,25	9	18,55	8
Set4-10	13	9	39242	2	8	46,15	8
Set4-10	13	10	101903	1,8	8	112,63	8
Set4-11	13	8	13620	2,38	9	13,07	8
Set4-11	13	9	14976	2,11	9	16,29	8
Set4-11	13	10	71714	1,9	8	76,32	8
Set4-11	12	9	15343	1,67	34	16,77	8

7.5 Conclusions & Further Research

In this part, I have dealt with the short term scheduling of a station in an aeronautical final assembly line. This problem can be classified as a Time Constraint Scheduling Problem. This problems have been frequently dealt with in project scheduling literature. In the literature review, I have gone through the main existing models for the more general RCSP (resource constraint scheduling problem). As a result, I have chosen to develop an Event Based Formulation for this problem. To do so, I have dealt with general temporal constraints, maximal and minimal time lags and multimode scheduling. This problems had been rarely addressed on their own in the existing literature and no exact method references have been found dealing with them together. Due to this features, the two new formulations we have developed are a contribution not only for the aeronautical industry but also for general scheduling.

The computational results from Section 7.4 have proven that the model is able to solve up to optimality small instances. As well as this, they have enabled as to make a comparative study between the two event based formulations: SEE-M and OOE-M formulations. The results of this comparisons are coherent with the ones reported by Koné for the original model [Koné et al., 2011].

Howevr, in order to extend it to bigger instances, it is necessary to improve the solver performances. Both SEE-M and OOE-M formulations have a number of constraints that grows as $(O(E^2W))$ where E is the number of events and W the number of work tasks to be scheduled. From the computational results it can be said that most of the instances can be solved with less events than the established upper bound of $W + 1$ for SEE-M and W for OOE-M. Therefore, the use of pre-processing to calculate the real needed number of events will lead to major performance improvements.

In that sense, a future research direction is the definition of a set of indicators that will help us for the characterization of instances from different final assembly line stations. This indicators would allow the development of more suitable and efficient pre-processing techniques. Also, those indicators should be useful for a pre-processing including a more accurate definition of the number of events.

Other future research opportunities include the improvement of the solution procedures by the introduction of decomposition or column generation techniques, as well as hybrid procedures including scheduling heuristics or meta-heuristics.

Constraint programming has also proven to be an efficient method for several combinatorial optimization problems, including scheduling ones. Therefore, one new current work is on the proposition of a global scheduling constraint, and associated filtering techniques, to solve the problem under study. CP solution scheme encompasses also constraint propagation techniques that can be used as pre-processing to calculate the relevant number of events; this issue would lead to major performance improvements. First results in this sense have been already been presented in [Borreguero et al., 2015]. A promising research direction is to propose hybrid MILP

/ CP larger neighbourhood search heuristic, as the one proposed for the MISTA challenge 2013 on the multi-mode RCSP by Artigues [Artigues and Hébrard, 2013].

Part V

Dealing with Uncertainty

In the previous parts, I have studied different aeronautical scheduling problems from a deterministic point of view. Nevertheless, as in any other industry, real operation occurs in a dynamic environment. Therefore, production managers need to handle daily disruptions that require changes in the initial schedule. In consequence, Part V is dedicated to the study of different options to deal with those unexpected events.

The first chapter of this part, Chapter 8, is dedicated to a double state of the art. To begin with, section 8.1 goes through the main uncertainty sources in aeronautical manufacturing. It includes information on the data availability for those disruptions. The following section, 8.2, presents the literature review. It describes the existing strategies to deal with uncertainty in the scheduling literature: sensitivity analysis, proactive scheduling and reactive scheduling. The first two intend to choose an initial schedule as robust as possible. Reactive scheduling repairs the schedule once disruptions have occurred.

After the reviews, I selected to apply sensitivity analysis and reactive scheduling to the aeronautical industry. Both strategies are applied to the airframe short term scheduling problem presented in Part II. Nevertheless, those approaches could also be extended to the other problems studied in this thesis.

Chapter 9 uses Discrete Event Simulation for a sensitivity analysis. By means of it, I have compared the performance of a set of detailed schedules and disruption management strategies. Chapter 10 uses reactive scheduling to come back to the initial schedule whenever there are parts arriving to or leaving the assembly line.

To end with this part, conclusions are presented in Chapter 11

INTRODUCTION TO UNCERTAINTY

8.1 Uncertainty in the Aeronautical Industry

Disruptions are part of the environment in almost any production system. The aeronautical industry, with its high complexity, is subject to continuous unexpected events. There can be many types of such disturbances. Vieira et al [Vieira et al., 2003] classified the main factors of disturbances in manufacturing systems in:

- Machine failure.
- Urgent job arrival.
- Job cancellation.
- Due date change.
- Delay in the arrival or shortage of materials.
- Change in job priority.
- Rework or quality problems.
- Over or under-estimation of process time.
- Operator absenteeism.

That classification is also enough to characterize the main disruption causes in the aeronautical industry. For a better understanding of the relative importance of each of those causes in that industry, I performed a series of interviews with production managers from different

manufacturing areas. I asked them to classify each of the causes in four categories: Very important, Important, Low Importance and Not Relevant. Material delay or shortage is among the most important for all the production areas. The under/over-estimation of process times follows. A little less important are the rework or quality problems and the operator absenteeism. Machine failures have low impact in final assembly lines, are more relevant for airframe assembly and important for part manufacturing. The same happens with changes in orders (cancellation, changes in job priority or new arrivals): they do not apply to final assembly lines, they are rare in airframe manufacturing and frequent in part manufacturing (specially in areas where they share series production and spare-parts manufacturing). These results have been summarized in Table 8.1.

Table 8.1: Disruption Causes in Aeronautical Manufacturing

Disruption Cause	Part Manufacturing	Airframe Assembly	Final Assembly Line
Delays and material's shortage	VI	VI	VI
Over/under-estimation of process time	VI	VI	I
Operator absenteeism	I	I	I
Rework or quality problems	I	I	I
Machine failure	I	I	LI
Due date change	I	LI	NR
Change in job priority	I	LI	NA
Urgent job arrival	VI	NA	NA
Job cancellation	LI	NA	NA

VI: Very Important; **I:** Important; **LI:** Low Importance; **NR:** Not relevant; **NA:** Not Applicable

Before taking uncertainty into account in the scheduling process, there is another main aspect that needs to be addressed. It is the poor quality of historical information regarding disruptions occurrence and its consequences. The degree of information available in the aeronautical plants I have studied is different for each of the disruption types:

- **Delay in the arrival or shortage of material:** Although all the information about materials is usually handled in ERP systems, and therefore their reception dates are tracked, the real need dates are not always registered in those systems. For example, in a final assembly line, materials will be usually requested on a batch basis (once per shift or week, depending on the cycle time). In consequence, the real impact of a theoretically late part is not known.
- **Over or under estimation of process time:** Processing times are usually calculated using MTM methods or experts' knowledge. Work orders are launched with that theoretical time calculation. Actual invested times are rarely registered. The booked hours in a work

order, which could be used to estimate the real invested time, usually include other inefficiencies not linked to the real process (for example, time spent looking for material, in meetings or in training).

- **Operator absenteeism:** Although this data usually exists it can be difficult to access (due to personnel data protection regulations). Moreover, it will not be straightforward to identify the real production area affected, as temporary movements between lines are frequent.
- **Rework or quality problems:** Aeronautical products are subject to high quality standards and legislation. In consequence, any issue affecting the product quality is usually well tracked. However, the time spent for its correction is more difficult to estimate. Furthermore, not only does this additional time need to be calculated, but also the time spent until there is a repair solution and the delivery lead time of any additional materials needed, which is usually not negligible.
- **Machine Failure:** Once again, even if the failures may be registered, the real lost time may not be easy to evaluate.
- **Job quantity and priority changes:** This information could be available. However, those are the least important disruption source as reported by production managers in airframe and final assembly lines.

Withal, the context in terms of information availability is changing. There was a first paradigm change due to Lean Implementation [Gastelum, 2002]. From that point on, standard sheets were commonly used and deviations were tracked and managed. Nevertheless, that information was not always easy to access nor stored over time. Industry 4.0 implementation and digitization are currently making a major change in this sense. In the last years, the amount of information available has increased considerably. Manufacturing Execution Systems are being deployed in most manufacturing sites, enabling a more accurate and extensive information registry. In consequence, even if results may not be accurate with today's data, conclusions from this chapter are specially relevant at this point in order to define what information could be needed for uncertainty management in near-future scheduling.

8.2 Scheduling Under Uncertainty: Literature Review

The literature about uncertainty in scheduling is rather sparse. The works from Vieira and Herroelen [Vieira et al., 2003] [Herroelen and Leus, 2005] have made a major contribution to build a common vocabulary for scheduling under uncertainty. Focusing on the way of addressing the uncertainty, the different approaches can be classified within three main categories: sensitivity analysis, proactive scheduling and reactive scheduling.

Sensitivity analysis consists on assessing the performance of existing schedules in different disruption scenarios. Those existing schedules are usually build before using deterministic approaches. Proactive scheduling takes into account the uncertainty at the moment of building an off-line schedule. It aims to deliver a schedule that is as insensitive as possible to uncertainty or remains feasible after disruptions. Main proactive techniques are stochastic, fuzzy scheduling and robust scheduling, who differ on the way they model the uncertainty. Finally, reactive scheduling faces the changes in a schedule once a disruption has occurred. It can use a baseline schedule or, in the cases with larger uncertainty degree, postpone all the decisions so that they are made in real time.

A more in detail review of the three approaches follows:

- **Sensitivity analysis.** Its strategy is to assess the performance of a baseline schedule created in a deterministic basis. Uncertainty is included in a second step, as a set of case studies. The impact that a change may have on a given schedule may be studied in two ways: using analytic sensitivity analysis or by means of discrete event simulation. Sensitivity analysis has been mainly studied for machine scheduling problems [Hall and Posner, 2004]. They address questions related to the changes that could be applied to the parameters of a scheduling problem so that the solution remains optimal. Also, they try to answer some of these questions without using the full details of the solution, which is of special relevance if we take into account that calculating feasible solutions may be extremely time-consuming or intractable in practice. A similar work would be relevant for project scheduling problems but, to the best of my knowledge, has not yet been published.

Another means of assessing the performance of a given schedule in case of disruptions is discrete event simulation. It is a form of computer-based modeling that provides an intuitive and flexible approach to representing complex systems. It models the operation of the factory as a sequence of events that occur at a particular time. The state of the system changes only when an event occurs. It has proven a useful technique for manufacturing systems analysis. In this case, it can be used for analyzing the performance of a given schedule once disturbances occur. Also, a set of mitigation strategies may be evaluated. [Cunha and Mesquita, 1996], [Kadar et al., 2004] .

- **Proactive scheduling** takes into account uncertainty during the construction of the baseline solution. Within this category, stochastic scheduling uses distribution functions to model the uncertainty of the parameters. For example, distribution functions are usually applied for activity duration, which is the most frequent source of uncertainty in scheduling. Demeulemeester provided in 2002 [Demeulemeester and Herroelen, 2002] an in depth analysis of the existing literature for stochastic scheduling.

Fuzzy scheduling is used when there is not enough historical data to determine a probability distribution for the uncertain parameters. That is usually the case of activities'

duration, that are frequently estimated by human experts. In consequence, the use of fuzzy numbers can be a more suitable alternative when it comes to modelling the length of the activities, instead of the distribution functions used in stochastic scheduling. Fuzzy scheduling makes use of membership functions, based on possibility theory. Behnamian [Behnamian, 2016] provided a survey on fuzzy job shop scheduling approaches. He reviewed more than 140 papers classified according to the shop floor environment: single machine, parallel machines, flow shop, job shop and open shop. In addition, Kahraman and Yavuz [Kahraman and Yavuz, 2010] published a more extensive approach on fuzziness applied to different production engineering and management problems, including machine and project scheduling.

Robust scheduling searches for a schedule that is less sensitive to stochastic disturbances, even if it is a non-optimal one. There are different techniques, as it can be read in surveys from Herroelen [Herroelen and Leus, 2005], Aytung and Lawley [Aytug et al., 2005] and Davenport and Beck [Beck and Davenport, 2000]. The most used are redundancy based techniques. As an example, Gao [Gao, 1995] extended the duration of the tasks whenever they use resources with a non-zero probability of breakdown. Moreover, Davenport et al [Davenport et al., 2014] introduced time slacks, not linked to activities, so that a same slack can be used as a buffer for different activities' delay. Resource redundancy is less used as it easily leads to cost prohibitive schedules. On top of this, different objective functions can be used. Tavares et al. [Tavares et al., 1998] used a risk function that combines the uncertainty on the project duration and the activity cost taking into account the redundancy chosen. Others focus on the expected objective function value. That is the case of Daniels and Kouvelis [Daniels and Kouvelis, 1995] who studied the single machine problem under the total flow time objective. To end with, Jensen [Jensen, 2001] included two other approaches: minimax objective and minimax regret. The former studies the minimization of the worst case performance in both absolute and relative terms. This results on conservative schedules. On the other hand, minimax regret defines the 'regret' for a schedule as the difference between the resulting cost and the cost that would have resulted from perfect information for that scenario. In consequence, the solutions obtained are less conservative [Kouvelis and Yu, 2013].

- **Reactive scheduling** means re-arranging the scheduling once the disruptions and inflows are known. This applies mainly to short term problems. In this case, at the moment of the decision, there is already a schedule in place. The constraints to be respected are different from the original ones and the objective pursued is also slightly different. Therefore, it leads to different problems than the original ones.

Reactive scheduling must address two main questions: when is a new schedule needed and how should it be calculated [Artigues et al., 2010b]. This topic has been extensively dealt with in the literature. Sabuncoglu and Bayiz [Sabuncuoglu and Bayiz, 2000] provided a

review on different reactive schedule techniques. Also, they compared the performance of a set of techniques for the classical job shop problem. Szelke and Kerr [Szelke and Kerr, 1994] focused on environments with frequent and high volume of uncertainty, where the off-line schedule is valid for a very short period of time and most of the decisions must be taken in real time. Vieira et al [Vieira et al., 2003] aimed to provide a framework for rescheduling literature. They included both strategies for repairing baseline schedules (partial rescheduling) and also for schedule regeneration (total rescheduling).

From these three approaches I have chosen to use sensitivity analysis and a reactive scheduling approach.

Sensitivity analysis has been performed by means of a discrete event simulation model, and is presented in chapter 9. Being able to envisage a schedule's performance was perceived as a powerful tool to choose between different possibilities when deterministic objective function values are similar.

Dealing with disruptions once production had started was reported as one of the major drawbacks for the implementation of the short term airframe scheduling model in the shop floor. Production managers felt it was not worth the effort needed to create a baseline schedule if afterwards there was not a similar tool to handle disturbances. As an answer to this concern, a re-scheduling approach was also deployed. It will be presented in Chapter 10.

Finally, the use of proactive scheduling was neglected due to two main reasons. To begin with, the scheduling models were already very complex without taking uncertainty into account. On top of this, due to the lack of good quality data, the deterministic + sensitivity analysis approach was more likely to have a real deployment than a proactive approach.

ROBUSTNESS ANALYSIS: DISCRETE EVENT SIMULATION

In this chapter I will use discrete event simulation in order to provide a sensitivity analysis for the short term airframe manufacturing scheduling case presented in Part II. The aim of the simulation will be to evaluate the effects of disruptions in a set of pre-defined schedules. To do so, I will use the optimal schedules calculated by the model explained on Part II. Nevertheless, the approach and the simulation model itself would also be valid for baseline schedules built otherwise.

9.1 Literature Review

Discrete event simulation is a form of computer-based modeling that provides an intuitive and flexible approach to representing complex systems. In discrete event simulation the operation of the factory is modelled as a sequence of events. Each event occurs in a particular moment of time. Whenever an event occurs and only when it occurs, the state of the system changes. Afterwards, the system remains unaffected until a new event occurs.

Discrete event simulation has proven a useful technique for manufacturing systems analysis. [Cunha and Mesquita, 1996], [Kadar et al., 2004]. In the case of the aeronautical industry, Scott [Scott, 1994] provided an early overview of the most relevant aspects for aeronautical assembly line simulations. From then on, most of the later references have dealt with problems related to final assembly lines.

During the define phase of an assembly line, the conceptual design is usually tested against a set of what if scenarios [Mas et al., 2013]. Discrete event simulation models can contribute to the evaluation of the expected performance, providing additional information to that on the industrial Digital Mock Up (iDMU) [Mas et al., 2015b]. Moreover, although process simulation

has been used more often in that early design phase [Jahangirian et al., 2010] it can also provide valuable inputs later in the life-cycle. As stated by Murphy [Murphy and Perera, 2002], it can provide quicker response time for decision making and evaluation of those decisions.

Several aeronautical industry case studies have been published up to now. Heike published a case study to compare the use of constant or variable cycle times within a flow shop [Heike et al., 2001]. Ziarnetzky [Ziarnetzky et al., 2014] used discrete-event simulation for analysing different inventory policies during a station of a final assembly line. It considers supplier and production disruptions. Lu [Lu et al., 2012] used simulation to identify bottlenecks and Noack [Noack and Rose, 2008] proposed simulation optimization for workforce balancing within a line.

Nonetheless, the literature is still surprisingly lacking of contributions discussing the utilization of simulation in airframe production. Neither has it been used to test operator management strategies, as is the case of this chapter. The test I will present can serve for a dual purpose: as a support during the design of the aeronautic production line and during the line operation.

9.2 Problem Description

I have modeled the airframe manufacturing process described In Chapter 3.1. It consists on an assembly line where four different variants of an airframe are produced. They all follow a fixed path divided in 9 production steps, as it is presented in Figure 9.1. Each process or production step is identified by a circled number in the figure. The manufacturing flow is not totally linear. Process 1 is done in cell C. Then, process 2 goes to cell A and from then on, the airframe follows a linear path from cells A to F. In some cases, such as in cell B, two processes are executed in the same cell (processes 3 and 4). There are five buffers that exist between different processes. In Figure 9.1, the buffers are represented by the triangles.

The objective of the simulation model was to help in the comparison of the performance of different theoretical schedules (as calculated by the model on Chapter 3.3) and also to evaluate the efficiency of different strategies to ensure on time delivery in spite of disturbances. As an example, in Table 9.1, I present two production options given by the model using 22 and 24 operators. Although both schedules result in the same production rate they differ on the number of operators and therefore, on the saturation of the workers within them. Choosing between the two options is not straightforward. The **Schedule-1** uses fewer workers. It leads to a higher occupancy, which on the one hand is more efficient if there are no disturbances but on the other has less free operator time in order to deal with the disturbances. On the contrary, **Schedule-2** uses more workers with lower occupancy but it is a loose solution where it is easier to deal with disturbances.

As it was presented in Chapter 8, from the nine possible disruption causes in manufacturing systems described by Vieira [Vieira et al., 2003], only seven were considered as relevant for airframe manufacturing managers. That classification is shown in Table 9.2. From this seven,

Figure 9.1: Plant Layout.

Table 9.1: Sample Options for the Production Schedule

Option	Early shift	Late shift	Test operators
Schedule-1	11	10	1
Schedule-2	12	11	1

due date changes and changes in job priority were assigned a very low impact factor. Therefore, I have not considered them in the simulation model.

Table 9.2: Disruption Causes in Airframe Manufacturing

Disruption Cause	Airframe Manufacturing
Delay's and material's shortage	VI
Over/under-estimation of process time	VI
Operator absenteeism	I
Rework or quality problems	I
Machine failure	I
Due date change	LI
Change in job priority	LI
Urgent job arrival	NA
Job cancellation	NA

VI: Very Important; **I:** Important; **LI:** Low Importance **NR:** Not relevant; **NA:** Not Applicable

The five most relevant disturbance causes have been taken into account as follows:

- **Delay in the arrival or shortage of material.** Two things can happen if there is a missing part for a process. Sometimes, the work on the airframe will go on and the work on the missing part will be done in a later phase, once it arrives. On the worst case, the missing part will block the airframe, that will be stopped until the missing part arrives. In that case, the jig will also be blocked, as the airframe will remain there. The workers will be released so that they can work in another order.
- **Over or under estimation of process time.** In Chapter 3.4, for the initial scheduling calculation, I explained that rounded production times were used. For example, the average time for process 2 of Model-A-LH was 6.7 hours and it was rounded to 8 hours. In the simulation model I will use the original (not-rounded) time: 6.7 hours. In addition, in the simulation a percentage of the processes takes more time than expected. This could be due to problems during the execution or to under-estimation of the process time. Nevertheless, both have been modelled as a single disruption source: process needing extra time.
- **Operator absenteeism.** The initial schedule is calculated taking into account a fixed workforce. The simulation model enables to load planned absences and also takes into account an average absenteeism rate. Whenever an operator is missing, he will not be available for a whole shift. The operators' absences cause delays during the simulation: if an operation must start but there are no operators available, then that operation is delayed and therefore all the other operations to be done in that jig afterwards.
- **Rework or quality problems.** Two different quality problems may happen:

Non-Conformities during any of the production processes. Due to them, an airframe may need some extra time to complete a task. In other cases, the airframe will be taken out of the assembly line for being repaired and brought back afterwards to perform the job.

Final Process Rejection. In the last process, airframes can be rejected. This rejection may result in minor or major repairs. Major repairs mean that the airframe will have to go back for the repairs to Process 5, which was one of the bottlenecks in the assembly line.
- **Machine Failure.** Whenever a machine has a failure, no work can be processed in it until it is repaired. Work-in-progress remains blocked until the machine is available again.

Other stochastic sources such as movement times (and the waiting time associated) were dismissed because of two main reasons. The first one was the low impact that they had in the daily work, according to production managers. Also, they were not taken into account because of the bad quality of the associated data which would have resulted in a non-accurate simulation.

As for the way in which problems are dealt with, the following decisions were made:

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Figure 9.2: Simulation Model Summary

- Work orders are never performed before their expected start date, even if both jigs, airframes and operators are available before.
- Work orders for the same jig follow a FIFO logic. They are always accomplished in accordance with their scheduled sequence.
- The theoretical number of operators per shift is part of the input data. It can be different to the scheduled number of operators. In consequence, more than the "theoretical" number of operators can be available to face disruptions.
- It will be possible to assign more operators to a task than the initially scheduled as far as the task can be done by a larger number of operators and they are free operators.

The simulation objectives and the disturbance sources that have been taken into account are summarized in Figure 9.2.

9.3 Simulation Model

The simulation was modeled using Simio Enterprise [Simio LLC, 2017]. Each airframe that is to be manufactured has been modeled as an entity. Each entity has to visit the different

Figure 9.3: Simulation 2D Model Display Snapshot

workstations spending a production time based on its type. Each operation requires an specific type and number of workers. In Figure 9.3, a snapshot of the 2D simulation model is presented, the Model-A are presented in light grey and the Model-B in dark grey. The operator is working in a Model-B-RH. There are three other airframes waiting in the buffer to be processed, and the work station in the left is idle.

The simulation model includes also a 3D view where the decision maker could follow the behavior of the system at different speeds and see how delivery delays begin to rise. He can see how the required variables are updated and where the airframe, the transporter and the workers are in each moment. (See Fig 9.4 for a snapshot).

9.3.1 Simulation Logical Diagram

The first step for creating the simulation model was to reproduce the path that follow the airframes in the assembly line. This logic path is shown in Figure 9.5. It differs from the plant Layout as here, duplicated jigs are represented one by one.

9.3.2 Job Order Simulation

The backbone of the simulation are the job orders. A job order implies that a task should be performed at a certain moment. The size of a job order is always smaller than half a shift. If a task has a longer duration, several consecutive job orders will be generated.

This job orders can be created from different sources:

Figure 9.4: Simulation Model 3D Snapshot

Figure 9.5: Simulation Model Logic

	Hora	Tipo Orden	No Workers	Num Orden	New	Last
► 1	36	Model A_LH	1	2101	1	0
2	40	Model A_LH	1	2101	0	1
3	8	Model A_RH	1	2201	1	0
4	12	Model A_RH	1	2201	0	1
5	88	Model B_LH	1	2301	1	0
6	92	Model B_LH	1	2301	0	1
7	56	Model B_RH	1	2401	1	0
8	60	Model B_RH	1	2401	0	1

Figure 9.6: Job Orders Created for a Sample Process

- **Source 1.** As an input from the baseline schedule. All the working requirements are transformed into job orders and launched at the scheduled time.
- **Source 2.** Due to an extra work requirement for a process. Whenever there is a non-conformity, a new job order for the repair work is launched.
- **Source 3.** Due to an unfinished job. Whenever the last planned shift ends, if the work is not finished yet, new job orders must be created.
- **Source 4.** Due to the correction work after the Final Process. If an airframe is rejected in the Final Process, additional works are required and, for that, new job orders are launched.

At the beginning of the simulation, the theoretical schedule is translated into job orders. Then, each job order is launched at its scheduled time. Figure 9.6 shows the job orders created as part on an initial schedule for one of the processes. It is a process that lasts 8 hours. In consequence, two consecutive job orders are created for each of the airframes. As an example, Model A-LH is processed in the initial schedule from hour 36 to hour 44. That has been translated into two job orders: one to be launched in the hour 36 and another to be launched in the hour 40. Another relevant information of the job order is the number of workers, included in the third column.

An order can only be executed once launched if all the necessary resources are available. That is: the jig is free, there is an airframe to perform the work in and there are enough available workers. To evaluate this, a combiner groups the job orders and the airframes. Then, the availability of resources (workers + jigs) is evaluated.

When there is no problem all the job orders created in the input state (source 1) run smoothly because they always find workers, jigs and airframes to perform their tasks. The problems occur when sources 2, 3 and 4 start to create job orders that cannibalize the resources. In addition, the availability of resources could decrease due to break downs or scheduled maintenance and, in the case of workers, due to scheduled days-off and absences. All the orders launched that are not attended remain in stand by waiting to be attended (following the pre-established job order sequence).

9.3.3 Job Order Execution Process

The Job Order Execution Process rules the sequence of events that take place once a job order + airframe arrive to a jig. Those events are as follows:

- A job order + airframe arrive to a jig.
- The availability of resources (operators) is checked. If there are no resources, the job order remains in stand by and the jig is blocked.
- If it is the first job order for that airframe in that jig, the disruption options are evaluated:
 - Machine Failure. If that is the case, the operators are released and the jig and airframe will stay blocked for the duration of the machine failure. Once repaired, the job order will be re-started as soon as a new operators are assigned to it.
 - Material Shortage: Blocking. If that is the case, the operators are released and the jig and airframe will stay blocked until the material's arrival. Once it has arrived, the job order will be re-started as soon as a new operators are assigned to it.
 - Non-conformity to be solved in the jig. If that is the case, an extra job order for that entity and jig will be launched. This had already been explained as source 2 of additional job orders.
 - Material Shortage: Non-Blocking. In this case, the job order continues. If the material has not arrived at the end of the process, a new job order will be launched in order to install the remaining parts as soon as they arrive and there are jigs and operators available.
 - Delay. Assigns extra time to the ongoing process.
 - Non-conformity to be solved outside the line. The non-conformity is solved by a new job order. The original job order is delayed until the non-conformity is completed.
- Then, the work starts to be done as soon as possible, evaluating each minute the remaining time.
- The combiner job order + airframe is released once the work is completed or if it has to be put aside until the arrival of a missing part or a non-conformity repair.
- In the last minute of the half shift, if a job order is not completed a new job order will be released for the remaining time, because the former job order is not any more valid for the next half shift.
- Whenever a job order is finished, the airframe will be released and will be paired to another job order from the next machine or from the same one if there was outstanding work.

This process is shown in Figure 9.7. In that figure, the part of the process that evaluates the machine failure has been highlighted.

9.3.4 Input & Output Data

Input data include information on the baseline schedule, task characteristics and the characterization of the disturbances occurrence. The input data were arranged so that they could be easily loaded using a MSExcel Data File.

The input data can be divided in two: the scheduled job orders and the disturbance information. The scheduled job orders must contain detailed information on their start time, length, operator profile and number, jig and airframe type. The disturbance information includes:

- Operators Absenteeism.
 - Not scheduled absenteeism rate per operator type. Probability distribution for the not scheduled absences.
 - Scheduled absences per operator type. Number of operators absent per profile, day and shift.
- Jig non-availability rate and solution time. Probability distribution for the failure occurrence and for the solution time per failure.
- Blocking material shortage rate & delay. Probability distribution for blocking material shortage and for the delay it causes.
- Extra time probability & duration. Probability distribution for the number of airframes that will require extra time and for the duration of that extra time.
- Out of the line non-conformity rate & solution time. Probability distribution for the occurrence of out of the line non-conformities and for the time needed for their repair.
- On site non-conformity rate & solution time. Probability distribution for the occurrence of on site non-conformities and for the time needed for their repair.
- Final process rejection rate. Probability distribution for rejections in the final process.

The most important output of the simulation is the on time delivery ratio. The number accumulated delay was selected as the main data used to evaluate the robustness of a solution. In addition to this, the delivery time per airframe is also saved.

Figure 9.8: Baseline Schedule for Simulation

9.4 Experimentation

The experimentation was done in an Intel Core 7 with 8 GB of RAM, using Windows 10 and the discrete simulation software Simio Enterprise [Simio LLC, 2017].

For the experimentation, three different baseline schedules were used. In all of them, the production rate is two Model-A airframes each four days, which was the production rate in the shop floor at the moment of the experimentation. For that production rate, schedule A is the result of minimizing the number of operators with the model presented in Chapter 3. It is a schedule that uses 10 operators. Schedule B is the result of setting the number of operators to 11 for the same production rate. Moreover, schedule C is the result of setting the number of operators to 12. As an example, the first days of the bar chart for schedule A is shown in Figure 9.8.

Each of the schedules has been tested against four disturbance scenarios. In all of them, machine failures occurred with 20% probability. All machine failures lasted for 8 hours. Machine failures happen only in processes 5, 6 and 7. Process 6 needed more extra time with a 20% probability. That extra time was always 6 hours. This data are summarized in Table 9.3.

The operators absence and the rejection rate had two different scenarios each (named as High and Low). In the low case, an operator is absent the 3.3% of its shifts, and 6.6% in the high rate. As for the final process rejection rate, in the low case airframes are rejected in 15% of the cases, and 30% in the high case. This data for each of the four scenarios are summarized in Table 9.4. In that table, each scenario is named after its absence and final process rejection rate: for example, the L-L scenario means a Low absence rate and a Low final process rejection rate.

On top of these 4 disturbance scenarios, 3 risk avoidance strategies were tested for each scenario and baseline schedule:

Table 9.3: Simulation Input Data Per Process for all Scenarios

Process	Machine Failures Prob	Machine Failures Duration	Ops. With Extra Time	Extra Time Duration
1	0%	-	0%	-
2	0%	-	0%	-
3	0%	-	0%	-
4	0%	-	0%	-
5	20%	8	0%	-
6	20%	8	20%	6
7	20%	8	0%	-
8	0%	-	0%	-
9	0%	-	0%	-

Table 9.4: Simulation Input Data Summary per Scenario

Scenario	Absence rate	Absence Value	Final Process Rejection Rate	Final Process Rejection Value
L-L	Low	3.3%	Low	15%
L-H	Low	3.3%	High	30 %
H-L	High	6.6%	Low	15%
H-H	High	6.6%	High	30%

- Baseline case, using the number of operator given in the detailed schedule.
- Extra workers case, using one extra worker during the early shift and another extra worker during the late shift.
- Night workers case, using two extra operators during night shifts.

In all, 36 experiments were run, combining the 3 baseline schedules and the 12 scenarios per schedule (2 absence rates x 2 rejection rates x 3 risk-avoidance strategies). Each experiment has been run 30 times.

The results in terms of accumulated delay have been plotted using a box and whisker plot. It includes the confidence intervals for the upper percentile, lower percentile and mean. The plots have been built using a confidence interval of 95%, with a lower percentile of 25% and an upper percentile of 75%. Figure 9.9 provides a legend for the box and whisker diagrams. Figures 9.10 to 9.12 present the box and whisker diagrams for each baseline schedule. Finally, figure 9.13 compares the box and whisker diagrams for the experiments on each of the 3 baseline schedules.

Figure 9.9: Box and Whisker Diagram Legend

Figure 9.10: Schedule A Simulation Box and Whisker Diagrams

Figure 9.11: Schedule B Simulation Box and Whisker Diagrams

Figure 9.12: Schedule C Simulation Box and Whisker Diagrams

(a) Schedule A Simulation Box and Whisker Diagrams

(b) Schedule B Simulation Box and Whisker Diagrams

(c) Schedule C Simulation Box and Whisker Diagrams

Figure 9.13: Box and Whisker diagrams for the 36 simulation scenarios

Baseline schedule A is the one with the lowest number of operators and therefore, the higher occupation. It is important to point out that in this case, using the baseline number of operators only an airframe is delivered on time in the less severe disturbance scenario (low - low). In the most severe situation, no airframe is delivered on time. The use of extra workers decreases the delay. In a high rejection rate scenario, despite the improvement of the performance, neither adding operators during the early and late shift nor adding a night shift are enough to obtain a good performance. No option delivers more than 50% of the products on time in this scenario.

Baseline schedules B and C perform better than A in all the scenarios. It is easy to see that this improvement is not only in terms of the mean accumulated delay but also in the dispersion of the results.

With regards to the risk mitigation strategies, in all cases putting the extra workers during the night shift presented better results.

Another relevant conclusion is that, with the same number of operators, it is better to use a less tight schedule than a tight baseline schedule and extra operators. For example, in the H-H scenario, baseline schedule A + Extra operators has a mean between 32 and 47 if extra operators work in early and late shifts and between 29 and 47 if the extra operators work on the night shift. For that same scenario and baseline B with no extra operators, the mean is between 27 and 47, which outperforms the other two cases. The value of the mean is also better than the other two. Moreover, the baseline case of option B delivers the double of units on time than option A with extra workers. Not only the mean is better, but also the behavior of this schedule against the different scenarios had tighter confidence intervals than schedule A with extra workers.

In the case of the baseline scenario C, using extra workers in the early and late shifts does not improve the results significantly. In that case, the existing available time of the workers is enough to make the most of the jigs' performance. Only using those extra workers in the night shift has a positive impact in the solution. Nevertheless, the baseline scenario C provides very similar solutions to those in baseline scenario B + extra workers in early and late shifts, that is an equivalent solution in terms of number of operators.

In general, the effect of the failures is hard when the problems occur in certain process and moments. In these baseline schedules, the takt time is 64 hours. The processing time of process 5 is 60 hours. This means that any problem or delay in this process will normally imply a late delivery. Also, the number of workers during the week is constant, but the real work schedule changes. If there is some operator absence in a day with a peak of work, its impact is higher.

Even though the number of failures due to machine failures and errors that require extra work does not change from one scenario to another, this is not constant in all the runs as a results to the stochasticity of the model. The number of failures has an impact on the severity of the run. The difference of number of failures among the scenarios will decrease as we make more runs for each scenario.

The results of this experimentation allowed the production managers to choose the baseline

schedule to be used and also the risk mitigation strategy. They have been used to provide an example of the benefits of simulation.

Nevertheless, further simulations can be still done to make the most of the existing model. The performance of all the baseline schedules calculated in Part II could be simulated and compared. Furthermore, some of the modeled sources of disruptions, such as material shortage and non-conformities have not been included in the current experimentation. They should be part of future experiments.

To end with, this experimentation results could be used to enhance the mid term scheduling model presented in Part III. If the experimentation was extended to all the baselines schedules, each of them could be associated an expected accumulated delay. The overall expected delay could be included as one of the criteria to take into account when deciding the yearly production plan.

9.5 Conclusions & Further Research

In this chapter, I have presented a simulation model that can help address the robustness of different theoretical schedules for the airframe assembly line studied in Part II. It evaluates the expected on time deliveries once disruptions occur. To do so, I have characterized the main disruptions that affect that line: absenteeism, material shortage, non-conformities and other process over-duration and machine failures.

A set of baseline schedules and risk avoidance strategies have been evaluated. The experimentation has proven that using fewer operators in the baseline schedule may sometimes lead to worst real performance once disruptions occur. Then, the cost of non-planned extra workers will be much higher than having included them in the baseline schedule. Moreover, in the experimentation, a baseline schedule with more operators outperformed the use of the same number of operators but distributed between scheduled and not scheduled tasks. Some of those results are not intuitive. Therefore, the use of simulation models can prevent managers from taking costly decisions.

The present experimentation could be easily extended to some disruption sources which have been modeled but not included in the experimentation. Moreover, it could be performed for all the baseline schedules calculated in part II. In addition, the simulation results can be used to assess the risk of late delivery associated to each schedule. That characterization could be then included as an additional criteria for the mid term scheduling presented in Part III.

In addition, although in this case I have applied discrete event simulation for short term scheduling in airframe assembly, this methodology can be useful in other steps of the supply chain and other moments in the aircraft's life-cycle. It can contribute to the evaluation of the build process design of the aeronautic assembly line in the initial phase. Once production has started, it can be useful to assess the impact and the convenience of, for example, changing for a faster or more reliable machine. In the mid term planning it could help us calculate the real throughput of

an airframe with the given resources or the resources needed for the desired throughput.

As a future work, I would like to extend the use of simulation to test the production process together with another processes of the plant, evaluating which option is better for each case.

As ad-hoc simulation models can be time consuming, another research direction can be to perform a high number of experiments in order to analyse the results looking for similar patterns. Those patterns would be there used to create decision rules for managers, so that they can make proper choices between baseline schedules without needing new simulations each time. One of those rules would be, for example, how to identify too tight schedules that must be avoided, such as the baseline schedule A in this case study.

Finally, the joint use of simulation and metaheuristics (simheuristics) has proven to be an efficient method to solve stochastic combinatorial optimization problems [Juan et al., 2015], [Cheng and Currie, 2004]. It could be an efficient method to address stochasticity in any of the aeronautical scheduling problems I have dealt with in this thesis.

REACTIVE SCHEDULING

10.1 Literature Review

This chapter is dedicated to reactive scheduling applied to the short term airframe assembly line problem. As it was stated in Chapter 8.2, reactive scheduling means re-arranging the scheduling once the disruptions and inflows are known. Vieira et al [Vieira et al., 2003] provided a framework for rescheduling literature. Their framework is based on three aspects: the rescheduling environment, the rescheduling strategy and the method, as shown in Figure 10.1

Rescheduling environments				
Static (finite set of jobs)		Dynamic (infinite set of jobs)		
Deterministic (all information given)	Stochastic (some information uncertain)	No arrival variability (cyclic production)	Arrival variability (flow shop)	Process flow variability (job shop)

Rescheduling strategies				
Dynamic (no schedule)		Predictive-reactive (generate and update)		
Dispatching rules	Control-theoretic	Rescheduling policies		
		Periodic	Event-driven	Hybrid

Rescheduling methods				
Schedule generation		Schedule repair		
Nominal schedules	Robust schedules	Right-shift rescheduling	Partial rescheduling	Complete regeneration

Figure 10.1: Rescheduling Framework, Vieira et al [Vieira et al., 2003]

In their classification, the environment refers to the set of jobs that the rescheduling must take into account. It is static if the set of jobs is known from the beginning and dynamic if new jobs arrived during the scheduling horizon. Within the static rescheduling, jobs can be deterministic or stochastic, depending on whether all their information is known. Dynamic rescheduling environments are classified depending on the arrival pattern (cyclic or not) and the differences between the process flows for the incoming jobs.

The rescheduling strategies are first divided into dynamic or proactive-reactive. They are called dynamic if no baseline schedule is generated and predictive-reactive if there is a baseline schedule. Moreover, predictive-reactive strategies differ on their rescheduling policies. They are called periodic if rescheduling happens following a periodical pattern, event-driven if there are specific events or disturbances that trigger the rescheduling and hybrid if both event-driven and periodical rescheduling is performed.

To end with, the rescheduling method must be considered. Two scheduling generation methods apply for dynamic strategies: nominal scheduling (if no stochasticity is considered) and robust scheduling (if stochasticity is considered). Predictive-reactive strategies result on scheduling repair methods. Those include: right shift rescheduling, regeneration and partial rescheduling [Abumaizar and Svestka, 1997]. Right shift rescheduling postpones every operation the amount of time needed to make the schedule feasible. Partial rescheduling reschedules only the operations affected directly or indirectly by the disruptions. It seeks to prevent nervousness, or ensure some stability in the schedule [Wu and Li, 1995]. Complete regeneration reschedules all the tasks, even if they have not been affected by disruptions.

For more detail in this classification the reader is referred to [Vieira et al., 2003] and, for a more detailed review to [Ouelhadj and Petrovic, 2009].

10.2 Problem Description

In Chapter 3, I presented a model formulation for the short term scheduling problem on an airframe assembly line. During the experimentation, I solved real instances in short time, which enabled the deployment of this model in the shop floor. However, when the solution was presented to real users, they had a major concern: scheduling update after disruptions.

As a reminder, the airframe assembly line studied had nine processes and five buffer positions. (See Figure 10.2). The scheduling solution consisted on a bar chart that indicated how many operators worked on each process during each half shift of the scheduling cycle time. (See Figure 10.3). This schedule could be also used to calculate the number of elements expected per shift in each buffer. For example, for the scheduling in Figure 10.3, in order to start the scheduling cycle there must be one unit of airframe ModelA-LH in the buffer between processes 5 and 6, another between process 6 and 7 and a last one in the buffer between processes 7 and 8.

However, during production, disruptions occur. In the case of major non-conformities, some

Figure 10.2: Airframe Assembly Line Plant Layout

airframes have to be taken away from the line, decreasing the number of airframes in the buffers. When coming back, those airframes also alter the expected number of units in the buffer. In consequence, production managers need to re-schedule in order to come back to the expected state of the buffers and be able to restart a cycle of the baseline schedule. Therefore, they asked for a re-scheduling model that would, given a status of the line (characterized by the number of airframes in each position, including the buffers), describe the activities to schedule in order to take the line back to the baseline schedule. That is, to the initial status of the buffers.

This re-scheduling problem can be classified as:

- **Rescheduling environment:** Static. Tasks will be rescheduled as if their number and duration were deterministic.
- **Rescheduling strategy:** Event-Driven. The trigger for the rescheduling is the difference between the expected buffer size and the real one.
- **Rescheduling method:** Partial rescheduling. The rescheduling solution is expected to affect as few production cycles as possible.

In summary, the problem can be stated as follows: given the current production status the model must provide a schedule within a given time horizon that returns the production line to the buffer state of the baseline schedule. The current production status is characterized by the number of elements in each buffer and the available resources for the scheduling period (jigs and

CHAPTER 10. REACTIVE SCHEDULING

Figure 10.3: Baseline Schedule Bar Chart and Buffer Size Calculation

operators). As this model will work for immediate scheduling, this availability of resources will be the real one for the coming shifts. Therefore they may be different from the availability data used when calculating the baseline schedule. These changes can be caused by, for example, scheduled maintenance for jigs or extra operator shifts created to minimize the disruption consequences.

10.3 Model Formulation

In order to calculate the new schedule, a MILP discrete time formulation has been developed. It used as a starting point the initial formulation model from Chapter 3. Although most of the parameters, variables and equations are common to the initial scheduling model, it will be explained thoroughly again for an easier reading.

Parameter sets (10 in total) are listed in Table 10.1. Table 10.2 includes all the model parameters and Table 10.3 the variables. Most of them are common to the baseline scheduling model. Nevertheless, their value will normally change, as only the processes needed to recover the baseline buffer will be scheduled.

The new parameters are displayed in blue in Table 10.2. They are the number of elements that re-entry the line after each process p , I_{ep} , and the number of elements that leave the line after each process p , O_{ep} . No new variables are added.

Table 10.1: Rescheduling Model: Sets

E	Set of elements e that are produced
P	Set of processes p that must be performed
K	Set of machines k
O	Set of types of operators O
O^P	Subset of operator types o that belong to a production category
O^{NP}	Subset of operator types o that belong to a non-production category
T	Set of time slots t
C	Set of cycles c in which the time is divided
C_e	Subset of cycles c of each element
T_{ec}	Subset of time slots t that belong to each cycle c of the element e

Table 10.2: Rescheduling Model: Parameters

Cycle times per element and time horizon	C_e LCM QC_e IT_{ec}	Cycle duration of each element $e \in E$ Lowest common multiple (of all C_e) Number of cycles for each element $e \in E$ in the time frame considered: LCM/C_e Initial time slot of the cycle c of element $ee \in E$
Element and processes characteristics	W_{pe} MAX_{peot} K_{pek} I_p	Workload (hours) to be performed to complete a process $p \in P$ of an element $e \in E$ Maximum number of operators of the type $o \in O$ for process $p \in P$ of element $e \in E$ 1 if process $p \in P$ of element $e \in E$ uses machine $k \in K$ and 0 otherwise 1 if process $p \in P$ can be interrupted and 0 otherwise
Precedences between Processes	$PR_{pp'}$ $IP_{pp'}$ $PL_{pp'}$ $L_{pp'}$	1 if there is a precedence relationship between p and p' and 0 otherwise 1 if there is a precedence relationship with zero time lag between $p, p' \in P$ and 0 otherwise 1 if there is a precedence relationship with at least a $L_{pp'}$ time lag between $p, p' \in P$ and 0 otherwise Duration of the minimum time lag between processes $p, p' \in P$ (hours)
Slot Definition	T M_t A_t N_t NN AL_{tp} PA_t NA_t	Slot duration (hours) 1 if time slot $t \in T$ belongs to a morning shift and 0 otherwise 1 if time slot $t \in T$ belongs to an afternoon shift and 0 otherwise 1 if time slot $t \in T$ belongs to a night shift and 0 otherwise Quantity of non-night slots 1 if in the time slot $t \in T$ it is allowed to work on process $p \in P$ and 0 otherwise Previous active time slot of time slot $t \in T$ Next active time slot of slot $t \in T$
Machine Availability	Q_k	Number of machines $k \in K$ that are available
Buffer Definition	$B_{pp'}$ $WB_{pp'}$	1 if there is a buffer between processes p, p' and 0 otherwise Weight value of each the buffer $B_{pp'}$
Entry & Out of the line	I_{ep} O_{ep}	Number of airframes of element $e \in E$ that come back to the line after process $p \in P$ Number of airframes of element $e \in E$ that go out of the line after process $p \in P$

Table 10.3: Rescheduling Model: Variables

Operators assignment per slot and element	o om_o oa_o o_{pet} no_{peot} ot_{ot}	Total number of operators	
		Total number of operators of type $O \in O$ who work morning shifts	Total numbers of operators of type $O \in O$ who work afternoon shifts
Slot assignment	s_{pet}	1 if there are operators working on process $p \in P$ of element $e \in E$ in time slot $t \in T$ and 0 otherwise	Number of operators of type $O \in O$ in time slot $t \in T$
	f_{pet}	Number of operators of type $O \in O$ in time slot $t \in T$	
WIP measure	b_{eppt}	1 if process $p \in P$ of element $e \in E$ starts in time slot $t \in T$ and 0 otherwise	1 if process $p \in P$ of element $e \in E$ ends in time slot $t \in T$ and 0 otherwise
	pb_{eppt}	Quantity of elements $e \in E$ that are in the buffer between processes $p, p' \in P$ during time slot $t \in T$	Quantity of elements $e \in E$ that are in the buffer between processes $p, p' \in P$ when production starts
Machine assignment	tb	Total quantity of elements in the buffers through the scheduling time horizon	
	m_{pekt}	1 if machine $k \in K$ is assigned to the process $p \in P$ of the element $e \in E$ in the time slot $t \in T$ and 0 otherwise	

The complete model is as follows:

$$Min. z = to \quad (10.1)$$

$$Min. z2 = Mtb + to \quad (10.2)$$

Subject to:

$$\sum_o \sum_t no_{peot} T = W_{pe} \quad \forall p, e, c | c \in C_e; t \in T_{ec} \quad (10.3)$$

$$m_{pekt} \geq o_{pet} \quad \forall p, e, k, t | K_{pek} = 1 \quad (10.4)$$

$$no_{peot} \leq o_{pet} MAX_{peot} \quad \forall p, e, o, t \quad (10.5)$$

$$\sum_o no_{peot} \geq o_{pet} \quad \forall p, e, t \quad (10.6)$$

$$o_{pet} \leq M_t + A_t \quad \forall p, e, t \quad (10.7)$$

$$\sum_{ep} m_{pekt} \leq Q_k \quad \forall k, t \quad (10.8)$$

$$ot_{ot} = \sum_p \sum_e no_{peot} \quad \forall t, o | o \in O^p \quad (10.9)$$

$$om_o \geq no_{peot} \quad \forall o | o \in O^p, t | M_o t = 1 \quad (10.10)$$

$$oa_o \geq no_{peot} \quad \forall o | o \in O^p, t | A_t = 1 \quad (10.11)$$

$$o = \sum_o (om_o + oa_o) \quad (10.12)$$

$$no_{peot} = 0 \quad \forall e, p, e, o, t | N_t = 1 \quad (10.13)$$

$$no_{peot} \geq o_{pet} \quad \text{if } t = IT_{ec} \quad \forall p, e, o, t | t \in T_{ec} \quad (10.14)$$

$$s_{pet} \geq o_{pet} - o_{pePA_t} \quad \text{if } t \neq IT_{ec} \quad \forall p, e, c | t \in T_{ec} \quad (10.15)$$

$$\sum_t s_{pet} = QC_e - \sum_{p' > p} I_{ep'} + \sum_{p' < p} O_{ep'} \quad \forall e, p \quad (10.16)$$

$$\sum_t f_{pet} = QC_e - \sum_{p' > p} I_{ep'} + \sum_{p' < p} O_{ep'} \quad \forall e, p \quad (10.17)$$

$$o_{pet} \leq s_{pet} + o_{pePA_t} \quad \forall p, e, t, c | I_p = 1; c \in C_e; t \neq IT_{ec}; t \in T_{ec} \quad (10.18)$$

$$f_{pet} \geq o_{pePA(t)} - o_{pet} \quad \forall p, e, c | t \in T_{ec} \quad (10.19)$$

$$f_{pet} * W_{pe} \leq \sum_{t' < t} no_{peot'} * T \quad \forall p, e, t \quad (10.20)$$

$$o_{p'eIT(ec)} = 0 \quad \forall e, c, p', p, t | P_{p,p'} = 1 \quad (10.21)$$

$$\sum_{t'} no_{peot'} * T \geq s_{p'et} W_{ep} \quad (10.22)$$

$$|IT(ec)| \leq s' \leq s \quad \forall e, p, p', t, cy | t \in T_{ec}; PR_{p,p'} = 1 \quad (10.23)$$

$$o_{pet} + o_{p'et+n} \leq 1 \quad \forall e, p, p', t, n | PL_{pp'} = 1; n = 0, 1, \dots, \frac{L_{pp'}}{T} \quad (10.24)$$

$$o_{peIT_{ec}} = 0 \quad \forall e, p, p', t, c | PL_{pp'} = 1 \quad (10.25)$$

$$f_{pet} = s_{p'es + \frac{L_{pp'}}{T} + 1} \quad \forall e, p, p', t | L_{pp'} = 1 \quad (10.26)$$

$$f_{pet} \leq m_{p'ekt+n} \quad \forall e, p, p', k, t | PL_{p,p'} = 1; K_{pek} = 1; n = 0, 1, \dots, \frac{L_{p,p'}}{T} \quad (10.27)$$

$$f_{pet} = s_{peNA_t} \quad \forall e, t, p, p' | IP_{pp'} = 1 \quad (10.28)$$

$$b_{epp't} = pb_{epp'} \quad \text{if } t = IT_{ec} \quad (10.29)$$

$$b_{epp't} = b_{epp't-1} + f_{ept-1} - s_{ep't} \quad \text{if } t = IT_{ec} \quad \forall e, p, p', t, c | t \in T_{ec}; BP_{pp'} = 1 \quad (10.30)$$

$$pb_{epp'} \geq 0 \quad \forall e, p, p' | BP_{pp'} = 1 \quad (10.31)$$

$$pb_{epp'} \leq QC_e \quad \forall e, p, p' | BP_{pp'} = 1 \quad (10.32)$$

$$tb = \sum_e \sum_p \sum_{p'} \sum_t b_{epp't} * WB_{pp'} \quad \forall e, p, p' | BP_{pp'} = 1 \quad (10.33)$$

$$o_{pet}, s_{pet}, f_{pet}, m_{pekt} \in \{0, 1\} \quad \forall p \in P, e \in E, t \in T, k \in K \quad (10.34)$$

As it was said before, the model very similar to the model used for the baseline schedule calculation. The only constraints modified are those in blue: (10.16) and (10.17). They are related with the number of times each process p of element e must be done. Whenever an airframe enters the line in process p , one unit less must be scheduled for the previous processes. By doing this, at the end of the scheduling horizon, one unit less will have arrived to the buffer immediately after process p . Instead of that unit, the incoming airframe will be used. On the contrary, if an airframe goes out of the line in process p an extra unit of each of the previous processes must be done. That extra unit will then replace the airframe that has gone out.

For this model, I have used a fixed rescheduling period equal to the original scheduling time horizon, LCM, which was calculated in Chapter 3 as the lowest common multiple of the cycles of each element (C_e). Once that rescheduling time horizon is set, there may still be different feasible solutions. Therefore, the same two objective functions from the original model have been used: minimizing the number of operators or the overall buffer. Another option would have been to use a variable rescheduling period and changed the objective function to the minimization of that rescheduling period.

The rest of the current model is as follows:

Objective Function Where the objective function can be (10.1) to minimize the used workers or (10.2) to the minimize the buffer size.

Workload and Machine Allocation per Process Constraint (10.3) ensures that the workload scheduled for process p of element e in all time slots t of a cycle multiplied by the duration of the time slots is at least the total process workload for that element W_{pe} . The simultaneous assignment of the machines and operators to the process of an element is guaranteed by constraints

(10.4). Constraints (10.5) and (10.6) refer to the operators that are assigned to a process. The number of operators of type o working on process p for element e in time slot t (n_{peot}) must be less than its maximum (MAX_{peot}) (10.5) and if operators are working on a process for a slot then an operator type must be assigned ($\sum_o n_{peot} \geq o_{pet}$) (10.6). Furthermore, per (10.7) operators only work on a process during a slot if this slot belongs to a morning or afternoon shift.

Machine Constraints The number of machines k that are assigned during a slot cannot be more than the machine availability Q_k per constraint (10.8).

Total Number of Operators The total number of operators that are needed per type and shift is calculated by (10.9). Constraints (10.10) through (10.12) limit the total number of operators, which is the sum of the morning operators (10.10) and afternoon operators (10.11). Operators are not permitted to work during the night shift per constraint (10.13).

Process Start and End When evaluating the first slot, a process begins (s_{pet}) when an operator (o_{pet}) begins working in this process 10.14. For the remaining slots, a process begins (s_{pet}) when an operator (o_{pet}) begins working and no operators were working in the previous active slot ($o_{pePA(t)}$)(10.15).

The number of times that a process begins/ends (s_{pet}) must take into account the number of elements to be manufactured (QC_e) and also the numbers of elements that come into the line and go outside, as it has been already explained (10.16- 10.17).

A process cannot be interrupted once it has started if non pre-emption applies to it per (10.18). To determine the end of a process, the value of $o_{pePA(t)} - o_{pet}$ is taken into account in constraint (10.19):

- $o_{pePA_t} - o_{pet} = 0$ if process p is active after both time slot t and its previous active slot or inactive after both.
- $o_{pePA_t} - o_{pet} = -1$ if process p starts in t
- $o_{pePA_t} - o_{pet} = 1$ if process p is inactive after time slot t and active in the previous active slot PA_t

Moreover, constraint (10.20) ensures that the end of a process can only occur if the addition of the prior workload is equal to the total amount that is required.

Precedence Relationships Precedence relationships are managed with constraints (10.21) to (10.28). Constraints (10.21-10.23) address general precedence constraints and (10.24-10.27) address time lag constraints (processes that must begin precisely n slots after their predecessor). Constraint (10.27) addresses the machine occupation during the time lag. Constraint (10.28) refers to a zero time lag precedence.

Buffer Allocation Constraints (10.29) through (10.33) refer to the buffer occupation during the time horizon. They are only needed if the buffer objective function is used. The buffer that corresponds to the first slot is equal to the quantity that the system uses to begin the production. The buffer of the subsequent slots (b_{eppt}) is equal to the number of the previous slot (b_{eppt-1} , b_{eppt}) and a balance of the income and output of this buffer in that slot change ($f_{ept-1} - s_{ept}$) (10.29 and 10.30). The initial value of the buffers of elements ($pbu_{f_{e,p,p'}}$) must be greater than or equal to 0 (10.31) and less than or equal to the number of elements that must be produced (QC_e) (10.32). Finally, the total number of elements through all the slots (tb) is equal to the weight sum of each buffer ($\sum_{eppt} b_{eppt} * WB_{pp'}$) (10.33).

Domain Constraints are 10.34.

10.4 Implementation

The model was implemented in AIMMS [Roelofs and Bisschop, 2011], using an Intel Core i7 pro with 8 GbB of RAM running AIMMS with CPLEX under Windows 10.

Two instances were tested: one for the case where an element is coming to the line with some tasks already done and another for the case where an element goes out of the line and therefore, some tasks need to be repeated. Both instances use the baseline schedule created for a cycle time of four days for the four elements.

In the first instance, there is a Model A-LH that comes back from non-conformity repair. It has a set of tasks already done: processes 1 to 5. Therefore, the resulting schedule must include this element, not launching that set of operations. The result is shown in Figure 10.4. In that figure, the red area shows the not scheduled tasks: processes 1 to 5 of Model A-LH.

In the second instance, an element needs to go out of the line for extra work. In consequence, additional tasks need to be scheduled to replenish the buffer position that is lost. The element that goes out is a Model A-LH, and leaves the line after process 4. In consequence, processes from one to four must be scheduled twice. Figure 10.5 shows the solution. The red area highlights the modified processes. Process 1 for Model A-LH is scheduled twice. The first one is done during the first shift and the last shift. The same happens with processes 2,3 and 4.

The solution time was less than 30 seconds for both instances. It is of the same order of magnitude as the solution time for the original model (that was solved in 15 seconds). That could have been envisaged, as the number of time slots is the same and also the number of variables. In consequence, the solution time will grow very fast with the value of the scheduling time horizon (LCM). For example, in Chapter 3, the two instances with LCM=24 were solved in 1300 and 2783 seconds respectively. This is something that must be taken into account as for the rescheduling the solution time needs to be shorter because at that moment production is already ongoing.

Another fact that has a negative impact on the performance is the selection of the rescheduling time horizon. In the previous two instances, the time horizon was the same as for the baseline

Figure 10.4: Rescheduling Solution with New Element Entry

scheduling. However, for some deviations more than a time horizon may be required to come back to the original status. For example, if a new equipping process for a Model A-RH must be scheduled, the new operation needs 52 process hours. A four day scheduling period has at most 96 available hours (working in the three shifts). In consequence, at least a 8 day rescheduling time horizon point is needed: that would enable 44 + 96 free hours for the new 52 hour process scheduling. Longer rescheduling time horizons would also be needed if more that a unit entries or exits the line.

This rescheduling time horizon was named match up point by Bean et al. In [Bean et al., 1991] they presented a use case where rescheduling is done for all jobs before a match up point and from there on the baseline schedule is used again.

The match up point definition can be done in two ways. The first one is to pre-define the number of cycles for matching up, as I have done in the present model (setting it to one cycle). A better option would be to make the model minimize the match-up point. To do so, I would define a new variable, m , as the number of cycles up to the matching point. The objective would be to minimize the value of m . Also, the number of processes to be done of each element will have to be multiplied by m , and therefore constraints (10.16) and (10.17) would be replaced by constraints

Figure 10.5: Rescheduling Solution with New Element Entry

(10.35) and (10.36):

$$\sum_s st_{e,p,s} = mQCY_e - \sum_{p' > p} I_{e,p'} + \sum_{p' < p} O_{e,p'} \quad \forall e, p \quad (10.35)$$

$$\sum_s fn_{e,p,s} = mQCY_e - \sum_{p' > p} I_{e,p'} + \sum_{p' < p} O_{e,p'} \quad \forall e, p \quad (10.36)$$

In fact, defining an adequate match-up point and rescheduling trigger is an issue worth studying in depth. Too long rescheduling periods can lead to worst performance. At the same time more frequent re-scheduling has a higher operation cost.

10.5 Conclusions & Further Research

Disruptions and unexpected events are a daily part of operations management. In any manufacturing system, production managers have to deal with those unexpected events. Small deviations are usually ignored or managed at operator level. However, major deviations may be harder to manage and moreover, hard to manage in an efficient way, so as to minimize their impact in the system's performance.

Rescheduling has been defined as the process of updating an existing production schedule in response to disruptions or other changes. This rescheduling can follow different strategies, depending on whether they use or not a baseline schedule, on the rescheduling trigger and the jobs affected by the schedule repair.

In this chapter I have gone through the rescheduling option classification presented by Vieira et al [Vieira et al., 2003]. Afterwards, I have chosen a predictive-reactive approach for the airframe assembly line short term scheduling problem. A MILP model has been presented and used for experimentation.

Predictive-reactive approach has been proven to be an adequate method for the aeronautical industry, where a baseline schedule is a must to coordinate the different lines but disruptions occur frequently.

Although rescheduling problems are different from the baseline scheduling ones, the model I have used shares most of the structure from the baseline scheduling model. That shared structure has advantages not only for the modeller but, most important, for the user, who will have similar data input and output structures. What is more, the similar data structure is also important if we take into account that for a full deployment of these models they must be integrated with information systems, and similar data structures would ease the implementation of both baseline and rescheduling models at a time.

The rescheduling strategy I have chosen uses a match up point approach, similar to that suggested by Bean et al [Bean et al., 1991]. Rescheduling is done for all jobs before a match up point and from there on the baseline schedule is used again. I have presented two instances in the implementation. Both of them were solved with a match up point of one scheduling cycle. Nevertheless, in other instances, a further match-up point may be needed. In fact, defining an adequate match-up point and rescheduling trigger is an issue worth studying in depth. Too long rescheduling periods can lead to worst performance. Nevertheless, more frequent re-scheduling can increment the cost and in some cases, it may be non-profitable. [Vieira et al., 2000b], [Vieira et al., 2000a],[Church and Uzsoy, 1992]). Hence, guidelines for trigger point and match-up point definition are some promising further research directions.

Final Assembly Line Short Term Scheduling Another possible research direction is to extend the rescheduling to other of the problems studied in the previous chapters.

For the case of the final assembly line short term scheduling, I had some interviews with production managers in order to check whether the rescheduling approach chosen in the airframe assembly scheduling problem would be suitable for them. After the interviews, I can conclude that there are relevant differences between the two problems.

In final assembly lines, the movement of an element from a station to the next one provides a natural match-up point. Any scheduling disturbances should be kept within that time horizon. Of course, sometimes that is not possible. If that happens, there are two main strategies: travelling work or larger time for the aircraft in the not finished station. The analysis of those alternatives

and their consequences has already been done by Heike et al [Heike et al., 2001] and Biele [Biele and Mönch, 2015].

Consequently, I focused on the rescheduling within the station time period. For that, the problem statement is as follows:

The **objective function** would be to minimize the differences between the new schedule and the original one. If possible, only partial rescheduling should be done, changing only the tasks affected by the disruptions. Both the changes on the starting dates and the assignment of the tasks to operators are to be considered as differences. Trade off between those kinds of differences was not clear for the interviewed managers. They stated that the relative importance of changes on due dates or resource allocation was linked to the structure of the station. For example, due dates changes should be avoided in stations with point of use material dispatching. Moreover, in stations with highly specialized operators, the resource allocation to tasks should be changed as few as possible.

The **constraints** to be taken into account include:

- Non-rescheduling time frame: changes in the schedule imply extra tasks for the support functions. For example, materials and tools need to be handled to the shop floor. In consequence, there is an initial time frame where tasks can only be scheduled if they already belonged to that time frame or where scheduled in the past.
- New operators and shifts: on top of the existing ones. This may lead to non-uniform shift distribution between operators.
- No change for some tasks: Some tasks may not admit any change even if they are scheduled outside the non-rescheduling time frame. For example: those requiring special skills that are frequently performed by shared resources. A change in those ones would have a major impact in other stations and/or lines that should be avoided
- Precedence graph actualization: During the real production, some of the defined precedence constraints may have been violated. This needs to be checked automatically before the rescheduling to avoid data inconsistencies and unfeasible rescheduling.

The baseline scheduling model formulated on Part IV could be used as a starting point for a rescheduling model. However, it must be said that for rescheduling, the performance requirements are higher as solutions need to be given in the range of minutes. Therefore, it seems reasonable to explore other solution methods, such as the constraint programming and metaheuristic approach that I suggested for a better performance on the baseline scheduling problem.

UNCERTAINTY CONCLUSIONS & FURTHER RESEARCH

In the previous parts of this thesis, I have dealt with a series of scheduling problems, applied to the aeronautical industry. They have all been addressed in deterministic approaches. However, real-world environment is dynamic and production managers need to face frequent unexpected disruptions. Although a baseline schedule is of high value for a more efficient production system, taking disruptions into account is also a must.

Therefore, this part has been dedicated to disruption management in the aeronautical industry. To begin with, I have characterized the main disruption sources that affect the different steps of the aeronautical supply chain. Afterwards, I have presented a literature review on common uncertainty scheduling approaches. They can be divided in three major methods: sensitivity analysis, proactive scheduling and rescheduling. Finally, I have applied sensitivity analysis and reactive scheduling to the airframe assembly scheduling problem.

Discrete Event Simulation has been used for sensitivity analysis. By means of it, I have tested the performance of a set of baseline schedules and disruption management strategies under real operation conditions. This has been proven to be a useful tool to help production managers run the system in the most efficient way in practice.

Even if the best strategies and baseline schedules are chosen, disruptions occur on a nearly daily basis. Production managers also need to have repair strategies to handle this disruptions during real operation. Therefore, I have also developed a model for airframe assembly lines' rescheduling and provided some hints of relevant aspects when developing a similar model for final assembly line stations.

The work presented in this part of the thesis contributes to bringing even closer to practice all the aspects I had previously presented on scheduling in the aeronautical industry.

Part VI

Implementation

In the previous parts, I have studied some of the main scheduling problems in the aeronautical industry. I have developed models that provide solution within an adequate time and tested them against real-industry instances. Gathering the data and requirements for building that real-industry instances and models has not been straightforward. In some cases, it has been nearly as hard as the building of the model itself.

Therefore, if we look forward to a real deployment of this models, they need to be integrated within the existing tool ecosystem. The growing digitization and implementation of Industry 4.0 only enhances that need. To do so, it is necessary to study the interfaces and data transaction needs between scheduling tools and other information systems. This interfaces need to ensure the coherence of the input data and, also, the use of the output scheduling data in all the other information systems.

Hence, the aim of this part is to provide some insights on how the developed scheduling tools interact with the major information systems existing in the aeronautical industry.

IMPLEMENTATION: TOOL LANDSCAPE AND DATA EXCHANGE

12.1 Digital Factory: PLM, ERP and MES systems

In the current Industry 4.0 context and digitization trend there are three main information systems that influence manufacturing related processes: Product Life Management systems (PLM), Enterprise Resource Planning systems (ERP) and Manufacturing Execution Systems (MES).

PLM systems were born from Computer Aid Systems, as an aid for engineering activities in the design phase. Computer Aid Drawing (CAD) systems became popular in the late 60s. Since then, more engineering activities and workflows have been integrated, evolving to the initial PDM systems and to the current Product Lifecycle Management (PLM) systems [Pardessus, 2004].

In parallel, in the manufacturing side, inventory control and material requirements planning (MRP) systems were introduced in the 1960s and 1970s respectively. Those systems widened with the incorporation of financial accounting and management systems. Nowadays, ERPs control nearly all resource planning and business processes of the entire enterprise, including areas such as human resources, project management, product design, materials, and capacity planning. [Umble et al., 2003].

When it comes to controlling day to day shop floor operations, ERP systems were not enough. As a result, Manufacturing Execution Systems (MES) emerged during the 1990s [Choi and Kim, 2002]. They support a set of shop floor execution activities, such as scheduling, order release, data gathering and quality control. [MESA International, 1997].

Those three information systems: PLM, ERP and MES are currently the most important ones with regards to manufacturing information in the aeronautical industry.

PLM systems have been present in this industry since the 1960s. Mas et al ([Mas et al., 2015a]

	Generation 0 1960	Generation 1 1990	Generation 2 2005	Generation 3 Future
Personnel/Skills	Loftsmen	Engineers	Concurrent Engineering teams	Collaborative Engineering
Engineering definition	Forms based data entry	Product Data Management (PDM)	Master Product Definition (MPD)	Integral Digital Mock-up (IDMU)
Product configuration	Explicit configuration	Multi-configuration	Mono-configuration	Configuration by specimen (Tail Number, MSN)
Mock Up	Physical mockups	Basic simulations	Advanced simulations	Full virtual manufacturing
Manufacturing	Manual work, templates	Automation, NC, CIM	Extended Enterprise (EE)	Digital Factory
PLM Tools	In-house applications	Customized commercial off-the-shelf (COTS), in-house applications		Software as a Service (SaaS)
Infrastructure	Mainframe systems	Workstations (UNIX)	Personal Computers (Windows)	Indifferent: PC, Tablet, Phone, virtualization.
Information Model	Basic surfaces and 2D drawings	3D wireframes, surfaces and 2D drawings	Solids, Model Based Definition (MBD)	Knowledge Based Engineering (KBE)
Data model format	Native: proprietary format			International standards
Data exchange format	Limited data exchange	IGES, SET and DXF	Native: proprietary formats	International standards
Long Term archiving (LOTA)	None exists, paper based	STEP (ISO 10303)		International standards

Figure 12.1: Aerospace PLM Key Topics
[Mas et al., 2015a].

provide a review on the impact that those systems have had in the European and North-American aeronautical industries. They include a summary of the key topics addressed by PLM tools for the aeronautical industry. That summary is shown in Figure 12.1. The early CAD systems were in-house applications that helped in the definition of basic surfaces and 2D models. Current PLMs are mainly COTs applications. With them, it is now possible to build all kind of solids and perform advanced simulations. The most recent trends include Digital Twins and Digital Factory modeling, that will enable an end to end tracking of the product, even during the in services phase. As for the systems itself, the need of better communication with other software was also identified by Mas et al. In that sense, they envisaged that future PLM generation will use international standards for data modelling and will evolve from COTs applications to Software as a Service (SaaS) systems. The benefits obtained with of the use of PLM tools and digital manufacturing in the aeronautical industry were also reported in a case study by Butterfield et al [Butterfield et al., 2007]. They stated that introduction manufacturing criteria in the design phase by means of digital solutions could lead to more than doubling the efficiency for workers carrying out fitting operations in an aircraft fuselage's assembly line.

ERP implementation for the aeronautical industry was discussed by Rashid and Mahmoud [Rashid and Mahmoud, 2008] in 2008. They drew the attention to aircraft manufacturing complexity and fast evolution, which make even more important the adoption of these kind of technologies. They also stated cultural change was one of the challenges related with ERP

implementation.

As for the deployment of MES, Yonus et al. [Younus et al., 2009] provide an example of deployment in an aircraft manufacturing subsidiary. They highlight the importance of MES for supporting real-time production control as well as data collection and reporting. In accordance with them, MES implementation had a positive impact in working efficiency, product quality and real time process monitoring of the products.

Nevertheless, PLM, ERP and MES cannot be dealt with as stand alone systems. In their origin, PLM systems were mainly linked to desing activities and ERP and MES to manufacturing and later stages in the Product Lifecycle. Following the MES growth in the last years, the standard ISA S-95 provided a framework for the standardization of the frontier between MES and other systems. That frontier analysis focused on the link between MES and ERP. From then, PLM tools have evolved from the design phase towards the concept of supporting digital manufacturing, offering advanced solutions for the industrialization stage. As a result, the borders of PLM, ERP and MES systems have become uncertain. In April 2008, Aberdeen Group performed a survey [Aberdeen Group, 2008] on 260 companies in the context of PLM integration with other systems. They asked the different companies where did they store their "manufacturing processes". It happened to be shared between ERP (36 %), MES (23 %), PLM (15 %). The other 26% store them in "another or system or not at all".

Within this tool ecosystem, planning and scheduling are part of a transverse process. Tasks related to line balancing begin very early in the product life-cycle, during the development phase [Lee et al., 2011] [Mas et al., 2013]. Decisions made at that stage have a strong impact in the future operation's performance. Afterwards, in the production phase, mid term planning and detailed scheduling are done. In fact, planning is within the core 11 functionalities for MES (as defined by the Manufacturing Enterprise Solutions Association), [MESA International, 1997]: Database management, IT Systems & Infrastructure, Technology, Troubleshooting, Testing, Implementation and Planning. They are represented in Figure 12.2. The term *Planning* here refers mainly to short term scheduling.

Therefore, planning and scheduling systems have interfaces with both PLM (more focused on the design phase) and MES systems. That double relationship to the definition and production phases is represented in Figure 12.3.

Nevertheless, in the next sections I will focus on the data exchanges needed for the planning and scheduling systems during the production phase.

12.2 Data Exchange per Scheduling Problem

From here on, I will focus on the data transfer to and from the planning and scheduling systems to the PLM-ERP-MES ecosystem.

Figure 12.2: 11 MES Functions [MESA International, 1997]

Figure 12.3: Context for the Planning and Scheduling Systems [Borreguero et al., 2016]

The PLM-ERP-MES ecosystem I will refer to is the one already deployed in the Spanish aircraft manufacturing sites from the previous case studies.

On the other side, when speaking about planning and scheduling systems, I will now focus on the models I have presented for short term scheduling problems (that is, Part II for airframe assembly lines and Part IV for final assembly lines). Even though aggregate production planning also requires an integration with the existing systems, it is used on a longer term basis. Therefore, having an efficient data exchange is less relevant. Furthermore, from the two aggregated planning models, the first one uses very little data. For the second, most of the information are the energy related parameters. Those are currently not available in any system and a far-reaching re-engineering would be needed to include them within the regular data flow.

Although most of the data are the same, there are some specific characteristic for the rescheduling compared to the initial schedule generation. Therefore, I will first address the baseline schedule generation and then the rescheduling.

12.2.1 Data Exchange for Baseline Scheduling

A common analysis can be done for the two short term scheduling problems. Figure 12.4 summarizes the data exchanges for the scheduling system. In that figure, the three main systems are represented: PLM, ERP and MES. Different colors are used for each group of data:

- The **blue boxes** represent the **Input Data that flows from the PLM and ERP tools into the scheduling tool**. That is:
 - **Manufacturing Process Data**. It contains the details of the tasks that must be executed. This includes the task code, duration and the resources needed: human resources (operators), jigs (in the airframe assembly case) and working areas (space). As I have already said, PLM, ERP and MES systems are currently suffering a deep transformation due to new Industry 4.0 requirements. In the PLM field, those systems are evolving to total Digital Factory and Digital Twin implementation [Ríos et al., 2016], [Mas F., 2013]. In consequence, manufacturing processes that used to be in the ERP are now being stored and managed in PLM and then exploited in MES systems (for example, 3D manufacturing process information) and ERP (for example, information on MBOM - manufacturing Bill Of Materials - to feed the MRP). A general overview on the impact of the digital manufacturing transformation can be found in [Chryssolouris et al., 2009]. In Addition, several papers from Mas, Rios et al [Ríos et al., 2016], [Mas F., 2013] deal with its direct application to the aeronautical industry.

As a result of this changing landscape, different information models coexist in the aeronautical industry. New tool sets and methodologies are being applied to recently launched projects while legacy programs benefit only from incremental changes.

However, the long product life cycle of the aeronautical industry makes impossible to neglect those legacy programs: the first A320 was delivered in 1988 and it is still one of the most popular models, with three aircrafts delivered per day and an A320 landing or taking off each two seconds [Airbus, 2019a].

For this reason, there is a double path for the main manufacturing process data (Task Code, HRRR needs (type, number), Workload and Machine requirements). Depending on the product's PLM tools maturity, this data will come from the ERP or directly from the PLM.

- **Cycle time**. ERP has that data for material requirements planning. It may be inaccurate and need some updates when scheduling.
 - **Planned Human Resource Capacity**. Number of operators and their specialty. That information is available in the ERP, within its core functionality.
 - **Precedence Graph**. Relationships between the different tasks. Precedence relations and time lags can be managed in some PLMs, as for example in CATIA-DPE. If that is the case, it is important to retrieve them. In this way, precedence information will flow from the manufacturing engineer in terms of the process definition, ensuring there are no knowledge gaps or duplicated information and tasks.
- The **green boxes** have been used for the **Input Data that is managed directly in the Scheduling Tool**.
 - **Additional Manufacturing Process Data**. On top of the information received from the ERP and PLM, there are other manufacturing process data used for the scheduling that are not registered in any other tool. Although most of this data are known at the moment of the process definition, they must be afterwards added by the scheduler, causing duplicity and failure risk. This information is the area allocation, the possibility to interrupt the process and the possible alternative modes for the task execution (in terms of profile or number of operators).
 - **Actual Cycle Time**. The Cycle time information coming from the ERP may be inaccurate and need some updates at the scheduling moment
 - **Machine Availability**. Historically, the number of available machines was not easily retrieved from ERP. Therefore, it is included directly in the scheduling tool. Nevertheless, in future, in PLM-Digital Factory it will be available and an automatic interface can be put in place.
 - **All constraints**. The precedence network must be completed in the scheduling tool. Even if some of this data may be coming from the PLM system, in most of the cases it must be modified during the scheduling process. This includes the most common end-

start precedence but also others such as non parallel constraints and area constraints (area definition and capacity).

- The **orange boxes** are the information that flows **from the scheduling tool to the ERP and back to the MES**.
 - **Detailed calendar per task**. Start and end dates and shifts. This information needs to be sent to the ERP, so that material requirements can be updated. At the same time, it must be sent to the MES, so that it can be shown in the daily production tracking. Normally, one of the main functions of MES are digital bar charts or performance tracker where the manufacturing progress per task is compared with the actual progress.
 - **Human Resources Number and Profile**. Number and type of operators that will do the task. This information is needed by the ERP, where the production orders are stored. Manufacturing Execution Systems also uses it to know the operator needs per day. However, information may flow to MES from production orders launched by the ERP instead of directly from the scheduling modules to the MES.
- To end with, **brown boxes** have been used for the information that is **not needed outside MES but is exchanged with other MES tools or functionalities**.
 - **Human Resource allocation**. I previously stated that HHRR data is sent to the ERP to update work orders. However, the resource allocation in terms of resource index (mechanical-1, for example) is only needed within the MES, for production tracking.
 - **Machine allocation**. For airframe scheduling, the allocation of work orders to each of the machines needs to be addressed. As it happened with the machine requirements, this information is not handled in the ERP, so it must be sent from the scheduler to the production tracking module.

As an example, the link between those data categories and the parameters from the input parameters for the short term scheduling model for airframe assembly line is presented in Table 12.1. The list of parameters used is that of Table 3.3.

Figure 12.4: PLM-ERP-MES Scheduling Data Exchange (Baseline Scheduling)

Table 12.1: Relationship Between Baseline Data Groups and Short Term Airframe Assembly Line Model Parameters

Group	Data	Parameters
Manufacturing Process Data	Task code and designation	iDMU and ERP
	Max-Min number of operators	MAX_{pet}
	Workload	W_{pe}
	Area	NA
	Machines	K_{pek}
	Interruptible	I_p
Resource Availability	Planned Human Resources Capacity	
	Area capacity	NA
	Machines	Q_k
	Buffer	$B_{pp'}$
Precedence Graph	Precedence Graph	$PR_{pp'}$
	Non-Parallel constraints	NA
	Maximal - Minimal Time Lags	$IP_{pp'}, PL_{pp'}, L_{pp'}$
Cycle time	Cycle time	C_e, LCM, QC_e, IT_{ec}

12.2.2 Data Exchange for Re-Scheduling

Once production starts, the scheduling environment changes. This has been thoroughly explained in Chapter 10. In consequence, new data needs to be taken into account and other data sets have to be replaced or updated. The data exchange for this stage is represented in Figure 12.5.

- **Updated Input data from ERP and PLM** are shown using pink boxes
 - **Material Availability.** This data had not been taken into account before as before the start of production all the materials are expected to arrive on time. However, once production starts, an updated status of material delivery can be retrieved from the information stored in the ERP. Expected delivery dates for late materials can also be found.
 - **Updated Manufacturing Process Data.** At this stage, work orders have already been launched and scheduled. Moreover, knowing the updated production status is a must. That includes: the percentage of completion of the tasks in the baseline schedule, and the identification of the blocked ones. Blocking reasons may be incidences on the process or non-conformities on top of material shortage. Besides, non-conformities or late product modifications may lead to new tasks (inflow), that must be afterwards included in the updated schedule.
 - **Updated Cycle Time.** This input will be updated if there are major changes, due to takt time modifications or extra client requirements.

- **Updated HHRR Capacity.** Once production starts, there HHRR capacity available is more accurate. It may include changes due to planned absences or also extra shifts added to deal with disruptions.
- **Precedence Graph.** The input information related to the precedence graph is normally not updated. Any changes on it are made directly in the scheduling tool.
- The type of **Input Data that is managed in the scheduling tool** are the same. However, it needs to be updated by the scheduler. New constraints may be added for the additional manufacturing processes (inflow).
- The **rescheduling result is also sent back to the MES.** This includes Updated start/end dates per task and new resource and machine allocation.
- There is a new data exchange in the **interface between the scheduling tool and other MES tools.** The scheduling tool will still share the **HHRR and Jig Allocation** but at the same time it will have to receive information on the **blocked tasks due to incidences.**

All the data exchanges for baseline scheduling and re-scheduling for both short term models are summarized in Tables 12.2 and 12.3. Note that some of the data are only applicable for some cases. In both tables, MSP refers to the short term airframe assembly line scheduling problem from Part II and RCSP refers to the short term final assembly line scheduling problem from Part IV.

Figure 12.5: PLM-ERP-MES Scheduling Data Exchange (Re-Scheduling)

Table 12.2: Input Data Exchange Summary

Group	Data	Source	Baseline		Re-Scheduling	
			MSP	RCSP	MSP	RCSP
Manuf Process Data	Task code and designation	PLM or ERP	✓	✓	✓	✓
	Optimal number of operators	PLM or ERP	✓	✓	✓	✓
	Max-Min number of operators	Sched System (from PLM or ERP)	✓	✓	✓	✓
	Workload	PLM or ERP	✓	✓	✓	✓
	Area	Sched System (from PLM or ERP)	✓	✓	✓	✓
Resource Availability	Machines	PLM or ERP	✓		✓	
	Interruptible	Sched System (from PLM or ERP)	✓		✓	
	HHRR Capacity	ERP	Planned	Planned	Real	Real
	Area capacity	Sched System (from PLM)		✓		✓
	Machines	Sched System or PLM	Planned		Real	
Precedence Graph	Buffer	Sched System or PLM	✓		✓	
	Precedence Graph	PLM	✓	✓	✓	✓
	Non-Parallel constraints	Sched System (from PLM or ERP)		✓		✓
	Max - Min Time Lags	Sched System (from PLM or ERP)	✓	✓	✓	✓
	Cycle time	Sched System based on ERP	✓	✓	✓	✓
Production Status	% Progress per Task	MES			✓	✓
	Blocked tasks: non-conformities	MES			✓	✓
	Materials Availability	ERP			✓	✓
	Task code and designation	ERP			✓	✓
Process Inflow Data	Optimal number of operators	ERP			✓	✓
	Max-Min number of operators	Sched System			✓	✓
	Workload	ERP			✓	✓
	Area	Sched System				✓
	Machines	Sched System			✓	
	Interruptible	Sched System			✓	

PLM or ERP = Defined on PLM or ERP depending on PLM maturity. **Sched System (from PLM or ERP)** = Defined on Sched System, but the information is available from the moment the process is defined in PLM or ERP. **Sched System (from ERP)** = Defined on Sched System, but information available from the moment the process is defined if it is defined in PLM.

Table 12.3: Output Data Exchange Summary

Group	Data	Destination	Baseline		Re-scheduling	
			MSP	RCSP	MSP	RCSP
Manuf. Process	HHRR Allocation	MES	✓	✓	✓	✓
	Machine allocation		✓			✓
	Time allocation	ERP + MES	✓	✓	✓	✓
Manuf.Process Inflow	HHRR	MES			✓	✓
	Machine allocation					✓
	Time allocation	ERP + MES			✓	✓

12.3 Conclusions & Further Research

In the Factory 4.0 environment, it is not possible to think about scheduling models implementations on its own. Scheduling is included in the core MES functionalities [MESA International, 1997]. Moreover, in a digital manufacturing environment, MES systems are strongly related to both PLM and ERP systems. Therefore, the whole PLM - ERP - MES ecosystem must be studied as a whole.

In this part, I have provided some high level mapping on the main data exchanges between the scheduling models presented in the previous parts and PLM, ERP and other MES modules. From the scheduling models, I have focused on the short term scheduling ones from Parts II and IV), as they need a more frequent communication with the other systems. This high level mapping is enough to understand the communication needs and main interfaces.

Nevertheless, the current work could be extended to a more in depth analysis. Before a real deployment, work on the ontology of the three systems should be accomplished. In that sense, Sanfilippo and Kitamura published a recent issue on formal ontologies on manufacturing [Sanfilippo et al., 2019] and Smith and Becker provided a example of ontology for scheduling systems [Smith et al., 1997].

In the aeronautical industry, Harcuba and Vrba [Harcuba and Vrba, 2015] worked on the ontology for what they called flexible systems. One of their case studies is the assembly line of A350 aircraft. Morales, Mas et al have also recently reported some preliminary studies on ontologies for the specific case of aircraft manufacturing [Mas et al., 2019], [Morales-Palma et al., 2018]. However, they have only focused on the Line Balancing Process. In consequence, the models I have presented in this thesis and the data and system exchange overview of this final part are of great interest as a starting point to extend the ontology to the other planning and scheduling processes. In fact, that extension is one of the research directions to be explored after this thesis.

Part VII

Final Conclusions

FINAL CONCLUSIONS

As it was stated in the introduction, the current industrial context is suffering major changes, because of the emergence of Industry 4.0 and the growing process digitization. Given that situation, the aim of this thesis has been to close the gap between planning and scheduling research and its implementation in real use cases from the aeronautical industry.

At the beginning of the thesis, four research questions were identified. They have been answered through the different parts of this document. I will now summarize the main results with regards to each research question:

1. What are the relevant planning and scheduling problems within the aeronautical industry?

To answer this, I began this thesis with the aeronautical supply chain characterization. Three main steps were identified: part manufacturing, airframe assembly and final assembly lines. In each of these steps, the planning and scheduling processes were described. Problems from the mid term to the shortest term were taken into account.

Afterwards, those problems were classified within the existing scheduling problems in the literature. The *Aeronautical Supply Chain Planning and Scheduling Matrix*, shown on Figure 13.1 is the best summary of this characterization. That figure is one of the important contributions of this thesis. It enables to distinguish among four different planning and scheduling categories in the aeronautical industry and to easily make the link between the industrial problem and the literature that deals with it. Moreover, it has allowed to identify the existing research gaps for this industry.

2. From the relevant planning and scheduling problems, which of them have already been studied?

Figure 13.1: Aeronautical Supply Chain Planning and Scheduling Matrix (as presented in Figure 2.7)

My next step has been to perform an exhaustive research on planning and scheduling problems literature applied to the aeronautical industry. The published works were ordered in terms of the prior problem classification. As a result, the *Aeronautical Supply Chain Planning and Scheduling Matrix* was completed with the existing references per problem.

The literature review revealed that the **Assembly Line Balancing Problem** was the most studied one. Eight references out of fifteen were dedicated to it. Also, Biele et al had extended the initial work from Heike [Heike et al., 2001] to most of the relevant use cases [Biele and Mönch, 2018], [Biele and Mönch, 2015], [Biele and Mönch, 2019]. In consequence, it was decided not to address this problem within this thesis.

Although for the other three problems there were some existing references, I identified important knowledge gaps in each of them. Therefore, I decided to address all of them.

Within **Machine Scheduling Problems**, I focused on the short term scheduling problem for airframe manufacturing. Some insights on short term scheduling for part manufacturing have also been provided. It has all been presented in Part II.

Aggregate Production Planning Problems, using the use case of the mid term planning for airframe manufacturing have been covered in Part III.

To end with, the **Resource Constraint Scheduling Problem** for short term final assembly line scheduling has been studied in Part IV.

In Figure 13.2 I have included the literature review summary to the *Aeronautical Supply Chain Planning and Scheduling Matrix* and also highlighted the problems that I have

Figure 13.2: Thesis Parts within the Aeronautical Supply Chain Planning and Scheduling Matrix

addressed in each part of this thesis.

3. How can the not-studied problems be addressed?

Short term scheduling for airframe and part manufacturing (Part II). In Part II I have presented a MILP formulation that has been used to solve real instances from an aeronautical airframe assembly line with 4 product variants and shared resources. Solutions have been provided in adequate time for industrial implementations. In fact, both the solution time and the quality of the solutions are better than the ones provided by the existing expert-based scheduling methods. Moreover, I have used two objective functions: labor cost and inventory cost. The trade off between both is not straightforward. Hence, I have built a Pareto front. Factories are more and more exposed to a changing environment and this approach enables the user to adapt the final decision to the current state of the factory and avoid the most common approach of a weighted cost objective function.

Mid term planning for airframe manufacturing (Part III). Another MILP model has been used for the aggregate production planning of long term airframe assembly lines. In fact, two different approaches have been presented for that problem. The first one is a simple model that has been implemented using Ms Excel and Open Solver [Mason, 2012]. Nevertheless, it is of direct use in the shop floor. It proves that sometimes simple models can result in big contributions to real life operation. Moreover, it boosts the implementation also of the short term scheduling model in the shop-floor, as they are strongly linked.

On top of this, another enhanced model has been developed. It is also a MILP model. Sustainability criteria as well as additional labor features were included to the first model. Those two aspects are among the future research features that [Cheraghalikhani et al., 2019] identified in a very recent (2019) state of the art review for aggregate production planning problems. Furthermore, this other model it deals with energy price variation through the year, which had not previously been addressed in previous energy related scheduling works. In consequence, this second model is not only of interest in the aeronautical industry, but also in the research fields of sustainable manufacturing and general aggregate production planning.

Short term scheduling for final assembly lines (Part IV). The third problem that has been addressed is the resource constraint scheduling problem that results from the short term scheduling of final assembly line stations. Although some previous works had been referred to that problem, each of them had included different scheduling requirements. I had made an overall model, with all the known requirements. Two event based formulations were presented. Although only small instances were solved, the results are enough to identify future research directions and opportunities for solving real industrial instances.

Dealing with uncertainty (Part V). In all the previous parts, problems were addressed in a deterministic way. It is clear that uncertain events and disruptions are very relevant in the aeronautical industry. Therefore, dealing with uncertainty had to be included in this thesis. First, I have reviewed the most relevant uncertainty sources in the aeronautical industry and also the general planning and scheduling under uncertainty approaches. Afterwards, I have chosen the airframe manufacturing assembly line short term scheduling problem to test two uncertainty approaches: sensitivity analysis using discrete event simulation and reactive scheduling (rescheduling) by means of a MILP model. Both of them have been developed using real instances. Simulation allows production managers to choose between schedules of similar characteristics in terms of deterministic objective functions. From the results, I can state that sometimes slightly more expensive baseline approaches can have much better performance under uncertainty.

Rescheduling is also a must in production shop floor. It seems unreasonable to spend a lot of time or effort to get a baseline schedule without tools to handle unexpected new events and disruptions. In the model I have presented I have used a similar structure to that of the baseline scheduling model. That is important because it eases the model implementation in terms of data exchanges and also in terms of decision maker training.

4. **What additional features should be taken into account to ensure the solutions provided are valid for an industrial deployment?**

Parts II to V have presented valid models that can be used to provide solutions to real industrial instances. Although I have formulated models to cover general problems, they have been developed taking into consideration end-users' requirements from each process. This may not be enough to ensure their implementation thus. Another key issue for go-live implementation are the interfaces between the scheduling systems and the other information systems in the industry.

In consequence, Part VI has been dedicated to provide some insights on the needed data structure for this implementation. I have provided some research of the state of the art of the PLM- ERP - MES ecosystem in the aeronautical industry. Also, I have identified the main interfaces between the scheduling systems and PLM - ERP and other MES modules. I believe that is a first step towards a global ontology that can ensure data coherence. Only with that, it will be possible to make the most of scheduling digitization.

In summary, I have covered all relevant aspects related to the research questions, providing an in depth state of the art for scheduling in the aeronautical industry and contributing to close some of the gaps identified in the first literature review.

Moreover, there are other aspects that merit special attention:

- Although the models have been presented separately, all the work done for the airframe assembly line, provides a very holistic approach to that production step: the feasible baseline schedules are used for the mid term aggregate production planning. Then, short term schedules can be compared in terms of labor cost and inventory cost (with the deterministic approach). Furthermore, they can be tested with the simulation model taking into account disruptions and decide between schedules and between disruption management strategies. To end with, once disruptions occur and the baseline schedule is no longer feasible, a new schedule can be calculated with the rescheduling model. Altogether, the models can help the decision maker from mid term planning to the final airframe delivery. Moreover, the data structure and the coherence between the models help in the transition from one step to the next one.
- Taking into account the actual needs of flexibility in the industry, multi objective approaches are becoming more and more important. When several objectives are present, such as labor cost, inventory costs and energy used, the translation of everything to cost is not enough. Therefore, the study of Pareto fronts and other representations to enable the trade-off between different objectives, as I have presented in Parts II, III and V are a major asset for real industrial decision makers.

FUTURE RESEARCH Through the different chapters, several future research directions have been identified:

For **Machine Scheduling Problems**, the case of part manufacturing remains unexplored. Some works on that area arose in the literature review. Nevertheless, as it was seen in Section 3.5, some specific constraints for composite parts are challenging in terms of modelling. That is the case of shared autoclaves and limited lifetime for the raw materials. Moreover, those workshops deal with a bigger production rate. Hence, a MILP model may not be able to deliver solutions in the required time and hybrid methods or meta heuristics should be explored.

The sustainability conscious approach for the **Aggregate Production Planning Problem** could be extended to the other problems in this thesis. In all probability, green production will be a raising subject in the next years.

As for the **Resource Constraint Scheduling Problem**, the model performance needs to be improved. I have identified several research directions in that sense: to begin with, a further study on the structure of the instances can help select the most efficient methods for solving the problem. Not all the stations in an assembly line follow the same structure. For example, test stations have a high number of non-parallel constraints that are barely used in structural stations. Therefore, different methods may be suitable depending on the instance characteristics. To be able to distinguish them, a suitable set of indicators needs to be selected.

Among the alternative methods, the constraint programming tests we have already begun in collaboration with CNRS-LAAS are providing good results [Borreguero et al., 2015]. I hope some output from that research path will be available in the next months. Other possible methods will be the hybridization of constraint programming or MILP with meta heuristics, which have already provided good results in other scheduling problems [Artigues and Hébrard, 2013].

Scheduling research **dealing with uncertainty** is more and more frequent. In Part V I have presented both a discrete simulation model and a re-scheduling model for the airframe assembly scheduling problem. Discrete event simulation has proven to be a value adding method for testing the performance of baseline schedules when facing disruptions. A next step in this sense would be to use simulation and optimization jointly to provide more robust schedules from the first solutions. Moreover, in Chapter 10 only a preliminary introduction on rescheduling applied to the final assembly line problem has been provided. A model for industrial solutions in that sense would be a must, taking into account that some assembly lines have long cycle times during which schedules need to be at least weekly updated.

Besides, from the three uncertainty approaches I described (sensitivity analysis, robust scheduling and reactive scheduling), robust scheduling has not been addressed. The use of fuzzy methods to deal with production scheduling uncertainty should be investigated.

To end with, Part VI is only a very first approach towards a scheduling ontology that can enable the full integration of scheduling within PLM, ERP and other MES functionality. Advances in this field are a must in this Industry 4.0 environment.

In all, I believe this thesis really contributes to closing the gap between the planning and scheduling literature and its implementation in the real case of the aeronautical industry. To do so, I have provided a new framework to address planning and scheduling in this industry. At the same time, I have studied and provided solutions for new planning and scheduling problems which, to the best of my knowledge, had not been addressed and can be of interest also in other industries.

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